roceedings of the I·R·E

OURNAL of the Theory, Practice, and Applications of Electronics and Electrical Communication

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APRIL, 1945

VOLUME 33 NUMBER 4

he Institute of Radio Engineers

Proceedings of the I·R·E

Published Monthly by

The Institute of Radio Engineers, Inc.

VOLUME 33 — *April, 1945* — NUMBER 4

Helen M. Stote, *Associate Editor* • William C. Copp, *Advertising Manager*

Responsibility for the contents of papers published in the PROCEEDINGS rests upon the authors. Statements made in papers are not binding on the Institute or its members.

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Entered as second-class matter October 26, 1927, at the post office at Menasha, Wisconsin, under the Act of February 28, 1925, embodied in Paragraph 4, Section 538 of the Postal Laws and Regulations. Publication office, 450 Ahnaip Street, Menasha, Wisconsin. Executive, editorial, and advertising offices, 330 West 42nd Street, New York 18, N. Y. Price, $1.00 a copy. Subscriptions: United States and Canada, $10.00 a year; foreign countries, $11.00 a year. Changes of address (with advance notice of fifteen days) and communications regarding subscriptions and payments should be mailed to the Secretary of the Institute, at 330 West 42nd Street, New York 18, N. Y. All rights of republication, including translation into foreign languages, are reserved by the Institute. Abstracts of papers, with mention of their source, may be printed. Requests for republication privileges should be addressed to The Institute of Radio Engineers.

THE INSTITUTE OF RADIO ENGINEERS

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It has been repeatedly pointed out in the PROCEEDINGS that through close-co-operation and understanding between industrialists and engineers, each group may function more effectively and the public may be the corresponding gainer. Leading industrialists have accordingly been invited to present guest editorials which appear in the PROCEEDINGS in the form in which they are received. There is presented below such an editorial from the pen of the President of the Mutual Broadcasting System, a constructive pioneer in his field of endeavor and a student of engineering functions and needs.

The Editor

Let's Get Better Acquainted

EDGAR KOBAK

There is a story about the phoenix—that it rises in youthful vigor from its own ashes. I am sure the phoenix was an electronics engineer: or vice versa.

Out of this war, which has laid waste a vast section of the earth's surface, will rise a brave new world: we are all convinced of it. Equally, we are sure that this new world will have electronics at its core: because, from a whisper here and there, we of the general public know that the war and its devouring needs have been a challenge to engineers and scientists in electronics and only *they* know, today, how rapid progress has been; and what unheard-of marvels they have in store for us, tomorrow.

When the new day dawns, these inventions and creations in electronics will have to be applied to peacetime living and working needs. That will require another kind of ability and experience—the kind possessed by business leaders and executives. They will have the responsibility of helping to find the practical applications; to shape the devices to the needs; to envision and develop the markets.

The two groups of men, scientists and engineers on the one hand, and the manufacturing executives on the other, are interdependent in the building of this postwar, electronic world. Without scientific development, businessmen have nothing new to sell; and without markets, laboratory developments contribute little to the world.

Personally, I feel this interdependence very keenly. My own start in business was in the testing and servicing of electrical equipment; later as an engineering editor of *Electrical World* and one of the founders of *Electronics* magazine I became intimately acquainted with progress in the electrical and kindred fields, and wrote extensively on the subject. My own appreciation of the engineer's and scientist's role in human progress is very considerable; and I have devoted much time to promoting a similar respect in others.

I believe that this appreciation can be carried further; and that it should be supplemented by a reciprocal feeling on the part of the engineer for the work of the businessman. I can see the need for a closer meeting of their minds—for such meeting is bound to strike sparks from which will come more and more progress.

Therefore, I should like to suggest that as a matter of principle and practice, more scientists and engineers be invited to attend and speak at industry meetings and business conventions; and that more business leaders be given the opportunity to sit in on engineering meetings.

If I am not mistaken, this type of co-operation has been largely responsible for engineering's great contribution to our prosecution of the war; it can and should be the foundation for our future peacetime world. Given both shoulders at the wheel, no man can say what the limits to tomorrow will be—if, indeed, there are any limits.

Joseph R. Redman

Rear Admiral Joseph R. Redman, United States Navy, was born in California in 1891, and has devoted the major portion of more than thirty years to service to his nation in communications activities.

He was graduated from the United States Naval Academy in 1914, and in 1921 completed a special graduate course in electrical engineering at Columbia University.

His professional career has included submarine service; tours of duty as division radio officer on the battleship *New Mexico;* aide and fleet radio officer; engineer officer of the battleship *Colorado;* and shore duty at Washington, D. C., with the bureau of engineering and as chief of technical sections in the naval communications organization.

Admiral Redman has become an expert in dealing with the problems of radio frequency, and in 1932 was named as a technical advisor to the United States delegation to the International Radiotelegraph Conference at Madrid. In 1938 he served as technical advisor to the United States delegation to the Cairo International Telecommunications Conference.

Shortly after Pearl Harbor, Admiral Redman was appointed director of naval communications, a post in which he has served since that time, with the exception of an eight-month tour of duty as cruiser commander in the Pacific war zone.

He is a member of the Joint Communications Board, the Combined Communications Board, and the Board of War Communications.

Following the victory of the Allied Nations, it is to be hoped that the world will be at peace for many years. It is perhaps too much to anticipate an indefinite continuance of world tranquillity. And if war breaks out again, it is essential that the communication and electronic engineers of the nation shall have maintained so advanced a position in their art that aggression can be effectively repelled. Urging such continued peacetime activities for the engineering membership of The Institute of Radio Engineers, the Director of Naval Communications in the Office of the Chief of Naval Operations of the Navy Department of the United States has prepared a guest editorial addressed to the readers of the PROCEEDINGS, which editorial follows in the form in which it was received. It is commended to the thoughtful attention of the membership of the Institute.

The Editor

Postwar Engineering Defense Against Aggression

REAR ADMIRAL JOSEPH R. REDMAN, UNITED STATES NAVY

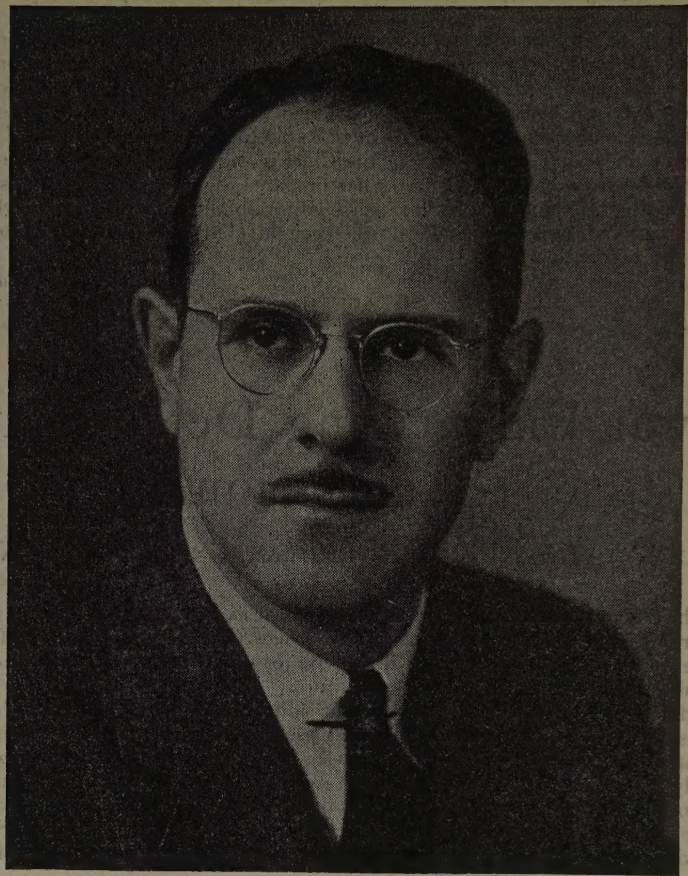
Wisdom is the application of knowledge gained from the experience of the past to preparation for the future. The current global conflict has presented many new problems, the solution of which is affording us a wealth of experience. After the war it will be wise for us, therefore, in the light of calm analysis to be guided by this experience in safeguarding our future.

Modern warfare has demanded that our scientific skill be matched against that of the enemy. In this competition of skills, the electronic art has proved itself a major weapon of offense and defense. The electronic industry and the radio engineer, faced with heavy responsibility, have proved themselves by responding nobly and in a measure that no layman can fully appreciate. Nothing would give me greater pleasure than to describe to you specific incidents of success which have been results of that response, but the security requirements of war continue to cloak secrecy on many activities. Some day I hope it may be my good fortune to depict the tangible and wonderful contribution of the radio engineer and the radio industry to the winning of this war.

The radio engineer by his very contribution has assumed a responsibility which must remain with him long after this war. It is a modern truism that there are no longer natural defenses to avail us. Oceans are traversed in hours, and the position of the United States has become no different from that of the many other nations who have lived for generations with potential enemies just across their borders. Concepts of reliance on natural protection, and of preparation for war after its declaration have of necessity been abandoned. Henceforth this nation must be prepared for vigorous defense at all times, which will require that our Armed Forces be kept in readiness with the necessary equipment and supplies available for immediate use. Electronic devices, as now demonstrated by experience, will be an increasingly vital part of this equipment of the future.

As complete demobilization cannot again be expected to accompany peace, so, therefore, must every manufacturer, executive, engineer, and workman bear the realization that he must continuously remain an important cog in the total mechanism of preparedness for defense at all times. The future must be characterized by the closest liaison between the Army and Navy, and between the Services and American Industry. Under the aegis of such co-operation new devices, especially in the field of electronics, must be constantly under development and test so that equipment may be kept ever current. Much of that work, too, must be done under the protection of security control so that no potential enemy may avail himself of it.

It behooves The Institute of Radio Engineers and each engineer as an individual, therefore, to live in awareness of the importance of his role and in realization of his responsibility for future years, a role and responsibility which will be discharged with the same high purpose exhibited in this war. It is to be hoped that the closest working relationship may be fostered and maintained at all times between this Institute and the Navy, for our missions cannot be accomplished independently of each other. Our mutual obligations to our Nation must be our first concern, with the skill of the radio engineer in the service of his country one of our first lines of defense. From our united efforts then will come those great achievements which will evidence to the world that unconquerable strength of the United States which stands ever ready to serve the cause of justice and freedom.



Herbert J. Reich

Board of Directors—1944

Herbert J. Reich was born on Staten Island, New York, on October 25, 1900. He received the M.E. degree from Cornell University in 1924, and the Ph.D. degree in physics in 1929. Since that time he has been on the staff of the University of Illinois, where he is professor of electrical engineering. On January 1, 1944, he was granted a leave of absence to join the staff of the radio research laboratory at Harvard University.

He has specialized in the field of electron tubes and electron-tube circuits, and has published approximately forty papers on these and related subjects in technical periodicals. He is author of "Theory and Applications of Electron Tubes," "Principles of Electron Tubes and co-author of "Ultra-High-Frequency Techniques

Professor Reich was elected to Associate membershi in 1926, and transferred to Member grade in 1941, an to Senior Member in 1943. He has served on the Boar of Editors, and on several committees, and during 194 he was a member of the Board of Directors.

Professor Reich is a member of the American Inst tute of Electrical Engineers, the American Physic Society, the American Association for the Advancemen of Science, and the Society for the promotion of Eng neering Education.

Address of Retiring President*

H. M. TURNER†, FELLOW, I.R.E.

As retiring president, I want to thank Dr. Austin Bailey and his committee for the splendid way they have planned and managed this convention. They have given freely of their time and energy for several months.

I extend to Mr. George Bailey, recently appointed Executive Secretary, a most hearty welcome to our staff.

During the past year the Institute lost by death a former president, Dr. Stuart Ballantine. Dr. Ballantine through his mathematical analysis and imaginative insight, advanced the science of radio and made important contributions to its literature. He will long be remembered as a brilliant mathematical physicist, an outstanding engineer, and a gentleman of winning personality.

In this world torn by strife we long for peace, but until it comes, our thoughts are with those who are serving our country. Members of the Institute are making major contributions to the war effort and for this many will receive high recognition. Some are making the supreme sacrifice as did Mr. B. J. Thompson, a Fellow of the Institute and member of the Board of Directors for eight years. Mr. Thompson was lost in the Mediterranean area, July 4, while on a special mission which was described as of "direct and vital importance to the war." He had served as an expert consultant in the office of the Secretary of War since December, 1943.

For many years I was associated with Mr. Thompson in Institute Affairs, and in view of his outstanding contributions through published papers, committee activities, and as a member of the Board, I desire to pay a tribute to him. He was a rugged individualist, in the best sense of the word. Once convinced of the justice and merit of a cause he was a fearless fighter in its behalf. He could and did present vigorous and convincing arguments in support of the principles to which he adhered. At the same time he was considerate of the opinions of others and always gave them thoughtful and respectful consideration. He was a highly original thinker, a natural analyst. To him a difficult problem was a challenge to which he applied impartial and penetrating logic. As associate research director of the Radio Corporation of America, he had unusual opportunities to apply his talents and creative imagination. He was an effective member of the committee which organized the Radio Technical Planning Board. In 1936 he was awarded the Morris Liebmann Memorial Prize for his development of electron tubes for use at ultra-high frequencies. His work extended the useful operating range of frequencies far beyond what had previously been possible. Mr. Thompson was recognized internationally as one of the foremost authorities in electronics. He was devoted to the Institute and those who knew him best will miss him most.

During the year the Board of Directors has had under consideration plans whereby our members may be better served.

The Institute has continued its sponsorship of the Radio Technical Planning Board which was very active through the year. Most of its thirteen Panels issued reports and participated as witnesses at a hearing held under the auspices of the Federal Communications Commission during the fall which lasted for several weeks. It is believed that the result of the comprehensive and intensive study which the Radio Technical Planning Board carried forward through the year will be of great help to the Government in making frequency allocations, as well as future considerations which will receive study at the next International Telecommunications Conferences. Not until the frequency assignments are made can industry proceed with the design of new equipment and formulate plans for production which will provide jobs in the postwar period.

A Committee on Education, of which Dr. Everitt is chairman, was appointed a year ago and the subject of postwar education has been discussed by eighteen Sections.

Committees under the chairmanship of Mr. W. C. White in this country and Mr. R. A. Hackbusch in Canada have studied the professional status of radio-and-electronic engineers, and have considered the very difficult problem of collective bargaining. Under our Constitution the Institute cannot function as a bargaining agency. The problem is further complicated by the fact that many of our members would be classified as employers and under present rulings would be disqualified from acting in the matter. Others would be subprofessional for whom professional engineers could not act. The committee has compiled information which is available to Sections.

Of especial interest to younger members is a plan providing opportunities for participation in Institute affairs for those who have not previously been active. A committee, of which Mr. E. Finley Carter is chairman, was appointed for the purpose of discovering the interests and special talents of members who might make effective contributions through serving on committees or in other capacities. A letter has been sent to all Section chairmen suggesting that local committees be formed to supply this information, which will be most helpful to the administrative officers when making appointments. These special qualifications will be utilized

* Decimal classification: R060. Original manuscript received by the Institute, February 1, 1945. Presented Winter Technical Meeting Banquet, New York, N. Y., January 25, 1945.

† Yale University, New Haven, Connecticut.

at the first opportunity. Committee workers provide a potential source of future leadership for the Institute. These Section committees will also assist the Admissions Committee by recommending qualified members from their sections for advancement to higher grades.

Despite travel difficulties and a heavy schedule I was able to visit about a third of our Sections during the past year. I was most favorably impressed with the energy, enthusiasm, and effectiveness with which the Sections are being operated. The work is well organized and is an important part of Institute activities. We discussed problems of mutual interest and I received helpful suggestions from the Section officers and members. One of the most frequent criticisms is the delay in handling applications and transfers. The delay has been due to several things, one of which has been eliminated. The Institute, in common with other societies, has for years published in the PROCEEDINGS, the names of applicants approved by the Admissions Committee before final action by the Board. The procedure has been more of a formality than a benefit as practically no objections were received. In view of this fact, I recommended that we dispense with such publication and this was approved by the Board. Thus, two or three months will be saved in acting on applications and transfers.

With reference to our members outside of the United States, the Board of Directors authorized the formation of a Canadian Council which will deal with problems of national interest within the Dominion. Mr. R. A. Hackbusch has provided the leadership in organizing the Council. It is likely that Councils will be set up in other countries. The Institute has acted as sponsor for the Canadian Radio Technical Planning Board. Mr. Hackbusch has been the guiding spirit.

During the year our Board of Directors has had conferences with distinguished representatives from England and Australia looking towards closer relations, and we have appointed a Liaison Committee of which Dr. Bown is chairman, to formulate plans for co-operation. Last May, I was privileged to have a small part, through a recording, in the celebration of the twenty-fifth anniversary of the Wireless (now Radio) Section of the Institution of Electrical Engineers in London. Opportunity has been afforded me to have informal discussions with engineers from the Buenos Aires Section regarding their activities. Recently word was received from the Paris Societé of Radioelectriciens that they are resuming activities after an enforced suspension of over four years, and wish to re-establish co-operative relations with the Institute. This was gratifying news. Greetings on this occasion of renewed activity were sent to them with an expression of our pleasure in their desire for co-operation.

Little progress has been made in standardization, due to lack of time. However, this is a matter that must receive early attention. In recognition of the rapid development in radio and electronics during the war and the important contributions made by our members, we were invited by the American Standards Association to nominate a director for their Board. Mr. F. R. Lack was named for the post.

The Buenos Aires Section, with our permission, has had IRE standards and papers, which have appeared in the PROCEEDINGS, translated into Spanish so as to be available to more of their members. We are appreciative of this compliment.

Formerly international agreement on standards was highly desirable; now it is a matter of the most urgent necessity. In our co-operative war efforts with Great Britain it is reliably reported that lack of uniformity in a single item increase the war costs $100,000,000 and what is even more serious, resulted in a delay that could ill be afforded.

With the increasing numbers of radio-and-electronic engineers in various parts of the country, the Board plans regional conventions and conferences, and is studying the problem to see how this can best be accomplished.

When restrictions on the publication of recent developments are removed a flood of papers will be available. The Board has very wisely set aside money for publishing these papers, probably in the form of extra PROCEEDINGS, as soon as they are released. In this way material can be made available to members at the earliest possible date.

We now have over 13,000 members and 33 Sections, six having been added during the year. The new Sections are: Cedar Rapids, Iowa; Dayton, Ohio; San Diego, California; Williamsport, Pennsylvania; and two in Canada—one at London and the other at Ottawa. Mr. Royden, chairman of the Admissions Committee, reports that his committee has acted on four times the usual number of applications. Increased membership gives the Institute greater opportunity for service and increases its prestige. However gratifying growth may be, at this time it presents many problems for the Board of Directors. The present office staff is much too small to handle correspondence and other business promptly. The office space is inadequate for present requirements to say nothing of contemplated expansion of service. Work on the new directory has to be done by our staff outside the secretarial office, as does that of the advertising department. Three months ago the Board room was converted into office space. We trust to luck in obtaining a room in other parts of the building for Board meetings. Next month through the courtesy of the American Physical Society we shall hold our Board meeting in their new headquarters. At present we have no rooms for committee meetings. Plans are now under way to secure space in some other building for the Editorial Department. With three times the membership, our space is only slightly greater than it was ten years ago. In 1943 a special committee was appointed to rent new quarters but after searching for six months without finding suitable space at reasonable rental, this committee recommended to the Board that we purchase a residence and

adapt it to our requirements, as was done by the American Physical Society. The Board authorized the committee to explore this possbility. Many properties were inspected during 1943 and 1944. Some offered definite promise but so far no commitments have been made. However, the Board is convinced that it will be to the advantage of the Institute to have a permanent home adequate to house the entire staff and has appointed a Building-Fund Committee to secure the necessary funds. Dr. Shackelford is the chairman and Mr. Coggeshall the vice-chairman. It is gratifying to report that many leaders in industry have accepted membership on this Committee and are giving it their enthusiastic support. The Initial Gifts Committee is operating under the chairmanship of Dr. W. R. G. Baker. Through the thoughtfulness of Dr. Shackelford, the Board of Directors were let in on the ground floor of his campaign and you will be interested to know that contributions from Board members averaged $217. It is a challenging program. Other societies with fewer members have accomplished more. The American Institute of Electrical Engineers had less than 2000 members when it started the project that, with the help of other societies, resulted in the Engineering Societies Building. I suspect that the total membership of the several groups was less than our present membership. The American Physical Society is much smaller than The Institute of Radio Engineers. The engineers of Dayton, Cincinnati, Detroit, and many other cities have succeeded in acquiring buildings for their activities. We engineers owe much to the Institute and now is our chance to contribute to the building fund. We must plan for the future. With radio and electronics, aviation, and chemical engineering destined to emerge from this war as the "Big Three," industries developed by the war, we should prepare now to grasp the opportunity that will be ours. Recently General Sarnoff of the Radio Corporation of America said, "the future of radio is always greater than its past." A membership of 25,000 is a possibility within a few years. By the end of this year we shall have as many members as AIEE had in 1936, and we are growing more rapidly.

With Dr. Shackelford and Mr. Coggeshall assisted by many others, I look forward with confidence to the success of this campaign and that a year from now Dr. Everitt will confirm this prediction.

Is Industrial Electronic Technique Different?*

W. D. COCKRELL†

Summary—**With the reduction in production of military electronic equipment it is logical for radio engineers to consider entering the field of industrial electronics. This junior branch of the industry differs from communication work especially in the emphasis on costs and the type of personnel available for operation and routine servicing. The range of industrial electronics extends from standard communication equipment at one end to the large pumped ignitron and multianode tanks capable of rectifying thousands of kilowatts.**

To Define Industrial Electronics

IN ORDER to give a logical definition of anything we specify the group to which it belongs and then describe the differences between it and the other members of that group. Thus, industrial electronics is definitely a member of the electronic family. Its essential elements are vacuum- or gas-filled tubes through which electrons flow. But the practical technique of operation, the personnel who must install, operate, and service it, and the economics which govern its design and construction will be found to vary somewhat widely from that found in the communication field.

Let us look back a moment at radio or wireless. It had its beginning in ship-to-ship and ship-to-shore communication. A more modern use has been the communication with airplanes. In both of these cases there is no practical substitute. The safety of the cargoes, the ships, and even the lives of the crew depend on adequate communication. Also, to provide better protection, it soon became necessary for some control to be emphasized over the rapidly increasing number of radio stations to prevent interference with each other. Therefore, it was only natural that the requirements for communication radio should be strict; that the government should exercise control over both the stations and operators; that the quality of the equipment should be a much more important consideration than its cost. Thus, each transmitter is licensed by the government only if it meets certain standards. Each operator must have an examination and, for the highest rating, must have had practical experience in station operation.

The Job to be Done

Let us next turn to the younger member of this pair, industrial electronics. To the layman this would seem to be the same thing except that the radio tubes were used for industrial purposes. But let us look more closely. Can these industrial jobs be done by other means? The answer is yes, in most cases. Often the alternate means is that of human operators who must do a monotonous task over and over all day long, but this has been done so

* Decimal classification: 621.375.1. Original manuscript received by the Institute, November 8, 1944. Presented, 1945 Winter Technical Meeting, New York, N. Y., January 26, 1945.
† Industrial Engineering Division, General Electric Company, Schenectady, N. Y.

long that it has become generally accepted, even by the ill-paid operators themselves, as necessary in the industry. This included such simple tasks as counting, sorting, inspecting, synchronizing, and regulating (Fig. 1).

Fig. 1—An electronic induction-heating unit.

There is competition in other ways, too. The speed of a motor may be controlled by rotating machinery and electromagnetic control. Some resistance welders may be timed by mechanical means. Alternating current may be rectified to direct current by any of a number of means.

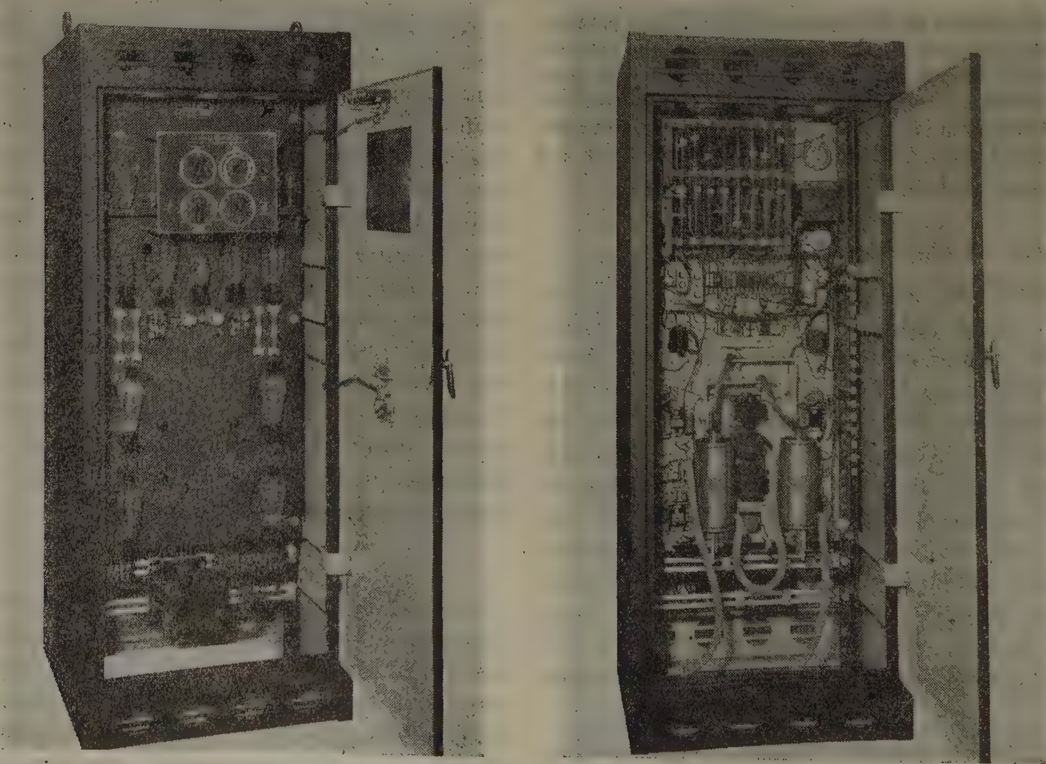
To hold its own in the industrial field the electronic equipment must do one of two things. It must provide a means for doing a job more economically than can b done in other ways, or it must do a job so much bett than can be done by other means that the extra cost wi be justified. It will be noted that, unlike radio whe reliability is the first essential, in both of the criteria fc industrial electronics the word "cost" is evident. Ever industrial electronic equipment then must not only do job but must do it within the required cost. This is pe haps the biggest difference between communicatio radio and industrial electronics: the large emphas which must be placed on all costs in the industrial fiel

However, do not be led to believe that all industri electronic equipments are small devices. Just as radi equipment covers the wide range from television statio and 500-kilowatt broadcasters to the crystal receivin set, so does industrial electronic equipment vary fro the multimillion-dollar rectifier installations which co vert literally hundreds of thousands of kilowatts c power to the small "electric-eye" unit and timing rela

The Men to Do It

After having glanced briefly at the equipment, le us now look at the personnel, the men who will instal operate, and service these equipments. Because of th emphasis on reliability in radio the operating personn as well as the station itself must meet minimum stand ards and be licensed. Furthermore, it has been foun necessary to have an operator on duty at all times whe the station is operating.

On the industrial front, we find a far different pictur The industrial user would like to treat his electroni



(a) (b)

Fig. 2—Front and back views of an electronic control for resistance welding.

equipment in the same manner as he does his electrical or mechanical equipment. Industrial electronic equipment must be so built that it can be installed by the average electrician as easily as a typical motor or magnetic-control panel. Usually it must be so designed that it can operate satisfactorily in whatever factory atmosphere it must be used. The typical American manufacturing system utilizes two types of personnel on their manufacturing machines. The highly skilled setup man "sets up" or adjusts the machines to perform the desired function so that the unskilled or semiskilled machine operator may perform the simple operation necessary for each cycle of operation (Fig. 2).

Thus, in an industrial plant the average operator at the machine generally knows little or nothing about the operation of the electronic equipment. Not only must the equipment be so designed that no incorrect operation on the operator's part can damage it, but it must also contain safety devices so that the operator cannot be harmed. Other devices such as photoelectric door openers or smoke detectors or precipitators must operate for weeks or months at a time without any supervision.

The Serviceman

And what about the servicing? Even in the best-designed equipment, tubes do burn out occasionally, vibra-

Fig. 3—One bank of electronic tubes controlling the lighting at Radio City Music Hall.

tion does break leads, and fuses do blow. This is perhaps the most difficult problem which we face today in the acceptance of electronic control. There are, of course, no licensed operators who have passed an examination on the theory of their equipment. There is rarely anyone in the plant from the chief electrician or plant engineer on down who had studied any electronic theory or knew anything about electronics beyond twisting the dial of his home radio until a year or so ago (Fig. 3).

If someone in his organization has been a radio "ham" the customer is indeed fortunate. Sometimes it is possible to hire the services of a local radio serviceman who

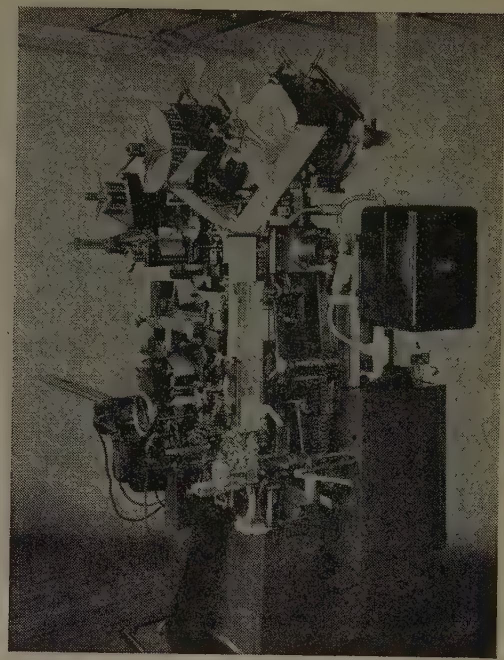


Fig. 4—A photoelectric installation designed into a packaging machine.

has studied and kept himself abreast of the times on industrial electronics. At other times it has been necessary for one or more members of the customer's electrical department to teach themselves how to service the equipment. Even then, he has been handicapped by lack of adequate text material. It is gratifying to note that within the past year much progress has been made in providing better material. The instruction books furnished with electronic equipment have also improved, but it must be remembered that at the present time, industrial electronic devices are not made in large quantities and the preparation of expensive instruction books cannot be justified if the equipment is to be built at a price at which it can be sold.

Some Industrial History

It will be noted that in almost every case we eventually return to the subject of cost and economics. This, again, emphasizes the extreme importance that cost must play in the industrial field. Industrial electronics had its serious beginning about 1930 and thus was forced to grow up in one of the most difficult times in the history of American business. This was a time of large man-power surpluses, a time when there was little money available for new investments and machinery. The attitude toward untried devices was extremely conservative. Thus, there was little chance of selling

equipment which could not promise a very definite improvement and even then, only in small quantities (Fig. 4).

No manufacturer had much money for development or promotion. Hence, progress was necessarily slow. Each new device or equipment had to prove itself before

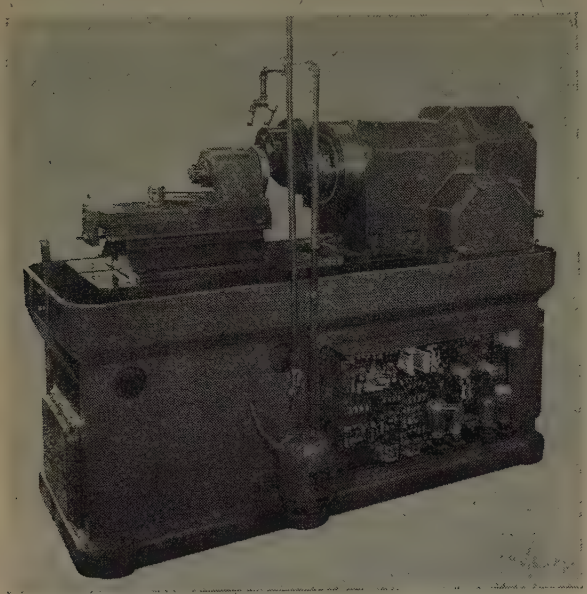


Fig. 5—Electronic motor control on a machine tool.

its use could be expanded. Some manufacturers ventured into this field, saw the long, heartbreaking road which lay ahead, and retired from the field. Other companies small and large, struggled on, plowing back their small profits into better designs and lower costs, and achieved a slow but steady growth in both the volume of their production and the acceptability by industry of their product. Much credit, too, must be given to those pioneer customers who purchased those first equipments. How well they knew the lack of adequate servicing and service instruments in those early days, the necessity for working the "bugs" out of new and untried equipment. It was early found that it was poor policy not to use the best material available, in the equipment in order to minimize the servicing requirements. The appearance on the market of cathode-ray oscillographs was a milestone in electronic servicing.

Just as the war gave an emphasis to radio engineering, it also assisted in industrial electronics. However, the assistance was more indirect than by actual government orders. The demand for planes and other equipment gave an added emphasis to the already rapidly growing field of electronic resistance welding. The demand for the ultimate in operation from machine tools provided an outlet for a rapidly increasing number of electronic motor controls. The use of standard units such as photoelectric relays, timers, and contact amplifiers increased rapidly. It is doubtful if sufficient aluminum and magnesium could have been produced without the assistance of the greatly increased number of power rectifiers (Fig. 5).

Many new manufacturers of electronic equipment for war use have sprung up during this period and many small manufacturers have expanded greatly to supply our war needs. It is expected with the return of peace that many of these factories will turn to industrial electronic equipment, so that it is anticipated that competition will be keen and that the customer will benefit by better equipment and a wider variety of equipment at lower prices.

The Classes of Equipment

What is meant by industrial electronics? With what kind of equipment will a man work who wishes to install and service it? Inside of the many factories which form our American industry he will find four classes of devices. The first includes the various forms of electronic communication equipment as useful here as elsewhere. In addition, there are three distinct classes of industrial electronic devices covering a wide range of uses.

Transplanted Communication Equipment

Electronic-communication equipment used in industry requires only a brief mention. It is radio- and audio-frequency equipment which has been adapted by industry for its own needs. In this classification may be included interphone systems, public-address systems, and carrier-current operation, both for communication and for relaying. This type of electronic equipment is familiar to every broadcast engineer and radio serviceman so that he should be able to install and service it without

Fig. 6—The sound-level meter.

any more study than that required to work on a new brand of transmitter or receiver (Fig. 6).

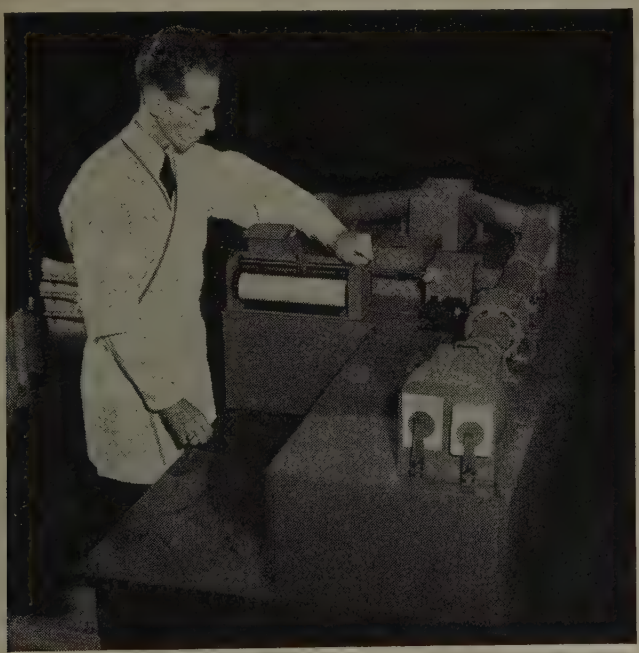
The precaution to be used in installing and the defects which need to be corrected and the complaints to be serviced will not be very different from those in any other type of radio or audio equipment.

Industrial Electronics

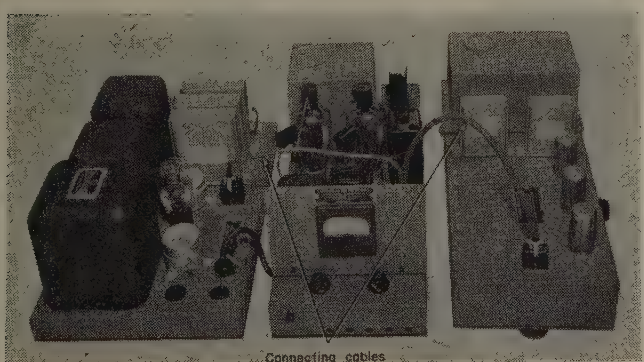
The Industrial Amplifier

This first class of industrial electronic equipment is somewhat similar. It comprises industrial amplifiers and oscillator units. Although the end use to which these equipments may be put will be new, the principles involved are familiar. The frequencies involved will be within the ranges with which the radioman has worked previously, and the precautions to be observed are also typical (Fig. 7).

However, included with the familiar circuits will be found some new and unfamiliar circuits which must be studied carefully both for themselves and for the unusual effects which they may create in the more familiar circuits. In this field the radio engineer who has kept up to date with the circuits used in television and radar will find himself much better prepared than his less wide-awake friend. Engineers who understand the operation of clipping, discriminating, scanning, and pulsing circuits will find themselves much more at home in this class of equipment. In this class we may include such things as oscillators for high-frequency induction and dielectric heating, elevator-leveling equipment, diathermy equipment, metal detection, etc.; amplifiers used for spectrophotometers, biological experiments, frequency and time standards, sound meters, etc.



(a)



(b)

Fig. 7—The recording color spectrophotometer and its tube units.

The Electric Eye and Many Others

Further removed from the communication electronics we find the second class of industrial electronic equipment consisting mostly of the small control devices. Here we find such commonplace devices as photoelectric relays, timers, and contact amplifiers employing only one or two tubes. These devices usually operate from raw alternating current on the tube plate or anode. Grid rectification is used in new and novel ways. Although the devices are simple, they require a new concept on the part of the high-frequency engineer, who must think in terms of a single cycle rather than in wave trains (Fig. 8).

Fig. 8—The chassis of a simple photoelectric relay.

Here, also, we first meet the grid-controlled gas-filled tubes, the thyratron and the ignitron. Control of these thyratrons by shifting the phase of the grid brings to light a whole host of grid-shifting circuits. Again, amplifiers which must respond to zero frequency or direct current bring a whole new set of problems.

Regulating circuits in which "hunting" of motors may occur require new concepts of oscillation in which mechanical devices form a part of the oscillating circuit.

A comprehensive understanding of the circuits of this class depends not only on a thorough understanding of tube theory, but also on a good working analogy of electrical-circuit fundamentals. To master this class of equipment the radio engineer must first acquire a firm foundation of electrical-engineering principles. This need not involve higher mathematics but it should include a working knowledge of the energy exchange and the fundamental properties of resistance, capacitance and inductance. Also, he must cover the transformer

and the effects of saturation, and the simple principles of the direct-current motor, if he is to service electronic-motor control or electronic-resistance welders.

Power Conversion

With this third class of industrial electronic equipment we become almost completely divorced from radio theory and practice. This is the large power-conversion equipment such as the ignitron and tank-type mercury-arc power rectifiers, inverters, and frequency changers.

Fig. 9—A large power-rectifier installation, output 60,000 amperes, 600 volts.

The fundamental theory of operation of these devices is usually simple. The rectifier, even the multiphase rectifier, is well known to every radioman. The inverter is simply a low-frequency oscillator using gas-filled tubes. The frequency changer is a combination of the rectifier and inverter. But, because of the sizes of these equipments and the amount of power involved, great emphasis must be placed on such things as maximum tube capacity, efficiency of operation, long life and reliability with minimum maintenance, and the effect of harmonics (Fig. 9).

A very important consideration, also, is the proper circuit-breaker protection for the rectifier, the transformer, and the alternating- and direct-current connected equipment. Since a power rectifier capable of supplying 5000 amperes at 600 volts direct current is a fairly common piece of equipment it may be seen that the power involved in a short-circuit fault on the direct-current system or failure of a tube to rectify can become tremendous.

The design and installation of this type of equipment would seem to be more in the field of the electrical power engineer than that of the radio or control engineer. Therefore, the radioman interested in this type of equipment would do best to obtain his training through central-station or power-utility sources. On the other hand, the improved design of the largest ignitrons to increase their current-carrying capacity and to reduce the number of possible "arc backs" or failures to rectify, is a challenge to the most expert tube designers.

Conclusion

Here is the broad field of industrial electronics, from the communication equipment, familiar to you all, to the power rectifier equipment, much more familiar to the power-house engineer. It is a new field with room for all. Given its first big boost by the needs of the present war it should have a lusty future and repay well the man who will study it seriously and do his part to help build it up. Even a year ago the means for instruction were very meager. Today there is a growing supply of source material for study and a growing need for the services of the men who will take that effort.

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Development of Electronic Tubes*

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Summary—The main types of modern electronic tubes are riefly surveyed in this paper, together with their general uses. Tubes re classified according to electronic mechanism, and their origin is raced to three independent sources and several independent lines f development.

The earliest group of electron-beam tubes made its appearance s the most direct result of intense scientific study of gas-discharge ubes prompted by William Crookes. These are: the Lenard tube 1894), the X-ray tube (Roentgen, 1895), and the cathode-ray tube Braun, 1897).

Another direct descendent of the Crookes tube is the mercury-arc ectifier (Cooper Hewitt, 1902) with all its modern derivatives, thyraron, phanotron, ignitron, and excitron. These are industrial tubes par xcellence and have become quite indispensable in many branches f industry. Their importance grows rapidly.

High-vacuum tubes, rectifiers, and pliotrons, through de Forest's udion (1908) and Fleming's valve (1904) are connected with the dison effect observed in incandescent lamps (1884). This vast amily includes kenotrons, and all radio and industrial high-frequency ubes. Ultra-high-frequency tubes stand apart in this class, since in heir designing electron transit time and associated ultra-high-equency circuits are two important factors to be considered. Special iodes (or tetrodes), magnetrons and velocity-modulation tubes are e main ultra-high-frequency types.

Finally, independent of all previous groups stands the phototube, nspectacular, but one of the most important tools in modern inustry. Its development is rooted in the photoelectric phenomenon bserved by Hertz and scientifically studied by Hollwachs (1888), y Elster and Geitel (1912), and others.

THE electronic tube is the heart and soul of every modern electronic application. In spite of the fact that electronics is the youngest branch of elecrical engineering and science, the electronic tube is uch older than ordinarily surmised. In fact, since Otto on Guericke's invention, 300 years ago, of his primitive acuum pump and electrostatic friction machine, many scientist has indulged in admiring the mysterious olorful phenomenon of gas discharge in an evacuated lass vessel. Among these was the great Faraday himself. he actual scientific study of this remarkable phenomeon was begun about 70 years ago by Wilhelm Hittorf, f Münster, Germany (1869)[1] and by a brilliant British hemist, William Crookes.[2] The latter's inspired lectures nd his paper prompted serious study of gaseous disharge throughout the scientific world. In fulfillment of rookes' vision that "here we shall find the ultimate uth", this study resulted not only in development of all modern electronics, but brought about a revolutionary electron theory of matter and changed the entire philosophical background of science.

Electron-Beam Tubes

The first practical result of universal study of Crookes' and Hittorf's "cathode rays"[3] in a discharge tube was the discovery of X rays by Wilhelm Roentgen,[4] Germany, in 1895. Their potential value for surgical, therapeutic, and even industrial purposes was quickly recognized by many. But it took almost 30 years to bring these ideas to full practical realization. An important contribution leading to the wide modern application of *X-ray tubes* in science, medicine, and industry was made in 1913 by W. D. Coolidge in this country; this was substitution of hot tungsten filaments for the original "cold" cathodes.[5] It coincided with a considerable improvement in vacuum technics which permitted exhausting tubes to the high degree of vacuum necessary for operating tubes at very high voltages.

Most of the modern X-ray tubes are diodes; the anode and anticathode or the target of early tubes are now combined in a single anode. However, the necessity of having tubes suitable for high-quality radiography and of guaranteeing maximum safety of operation makes the tube structure more complicated than that of a simple diode. Tungsten is the commonly used material not only for filaments but also for targets, because of its low vapor pressure, high melting point, high atomic number, and fairly good heat conductivity. For limiting the size of the "focal spot" on which the electrons impinge the small sturdy tungsten filament is mounted within a narrow slot of an electrostatically focusing cup. In order to prevent secondary electrons from bombarding the glass walls, modern tubes are frequently designed with *hooded* anodes.

The problem of cooling the anode is paramount with X-ray tubes as heat generation is confined to the limited area of the focal spot. With low-power tubes the tungsten target is simply supported by a molybdenum rod, and since heat is not readily conducted from the target, the latter heats up to a high temperature as the result of electron bombardment, and heat is radiated into the surrounding space. The other generally used method of cooling the target involves a design in which the target is embedded in the solid-copper anode usually by the process of high-vacuum casting. The heat is then conducted away from the anode by a copper rod

* Decimal classification: R330. Original manuscript received by e Institute, November 11, 1944. Presented, National Electronics onference, Chicago, Ill., October, 1944 (the Chicago Section of e Institute of Radio Engineers was one of the Sponsors of the ational Electronics Conference).

† Westinghouse Electric and Manufacturing Company, Bloomld, New Jersey.

[1] W. Hittorf, "On the conduction of electricity by gases," *Pogg., nn.*, vol. 136, pp. 1–31; January 27, 1869; pp. 197–235; March 2, 69.

[2] W. Crookes, "Repulsion resulting from radiation," *Phil. Trans.* l. 170, pp. 87–134; November, 1878; "On the illumination lines of olecular pressure and the trajectory of molecules"; pp. 135–164; ecember, 1878; "Contributions to molecular physics in high vacua"; . 641–662; April, 1879.

[3] This name was inaugurated by a German physicist, H. E. Goldstein, in 1876.

[4] W. K. Roentgen, "On a new form of radiation," *Electrician*, vol. 36, pp. 415–417; January 24, 1896.

[5] W. D. Coolidge, "A powerful Roentgen-ray tube with a pure electron discharge," *Phys. Rev.*, vol. 2, pp. 409–430; December, 1913.

extending the anode through the tube envelope and is dissipated into the surrounding medium, oil or air, by a "radiator", terminating the rod. With heaviest loads, such as in 220-kilovolt tubes for industrial radiography, circulating oil cooling is applied to a hollow anode. Water is not favored here on account of complications in high-voltage insulation.

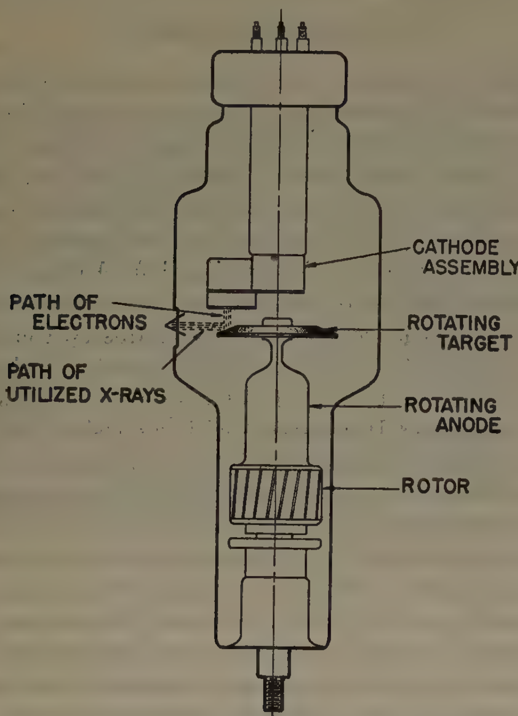

Fig. 1—Rotating anode X-ray tube for radiography requiring high X-ray output.

According to the intended use, X-ray tubes are designed for various operating voltages. For medical diagnostic uses voltage range is between 40 and 100 kilovolts. In medical therapy, tubes are employed up to 1,000,000 volts and even higher; usually they are continually exhausted in operation. For industrial radiography tubes are required from 30 to 220 kilovolts, and a 1,000,000-volt tube was recently employed by the General Electric Company for inspection of seam welds and castings in important apparatus.[6] These megavolt tubes necessarily have a complicated multisection structure for a more uniform distribution of potential gradient.

In some medical applications it is desirable to make radiographs of very short exposure times requiring high intensities of X-ray radiation, hence, high current density within a small focal spot. The answer to this is the tube with rotating anode, in which the focal spot, though stationary in space, rapidly changes its location on the periphery of the revolving target (Fig. 1). The anode is supported on ball bearings in vacuo; it forms a part of the rotor of an induction motor the stator of which is oil immersed and mounted externally to the tube. The outstanding problem in this type is to provide special lubricant effective at high temperatures in vacuo. This tube was designed in 1930 by the Philips Lamp Company of Holland.[7]

One of the important recent developments in the X-ray field is a cold-cathode tube for high-speed radiography, which permits taking pictures of objects moving with a considerable velocity, such as bullets in the barrel of a gun. The tube permits exposure of less than a microsecond, during which time a current of the order of 2000 amperes flows through the tube. To supply this enormous current an instantaneous metal vapor arc triggered between two cold electrodes is used as cathode. The tube was developed in 1940 by Slack and Ehrke.[8]

As another quite recent development, the Kerst tube, should be mentioned which gives a simple physical means to accelerate electrons up to 30,000,000 electron volts.[9] Its great value to science and some future practical application are beyond any doubt.

Another early outcome of scientific study of Crookes discharge tubes was the *Lenard tube*, the typical high-voltage cathode-ray tube, described by Lenard,[10] one year before Roentgen discovered X rays. The Lenard and Roentgen tubes can be viewed as sister tubes as to their general construction, production of electron beam, operating voltages, and even with respect to some of their applications. However, while the purpose of a Roentgen tube is to produce X-ray radiation by electrons impinging upon the target, the Lenard tube is designed to permit the electrons to pass through an extremely thin metal or glass window in the wall of the tube with as little loss of energy as possible and to become available outside the tube for bombardment of various objects. The thin window of the Lenard tube corresponds to the target in an X-ray tube. Thus far, Lenard tubes have been used mainly in biological studies of the effects of electron bombardment on living cells. There are, however, indications that Lenard tubes can compete with, or supplement X-ray treatment of ailing tissues in the human body because of the greater physiological effects of electrons. It may be pointed out that the recently developed Kerst tube can also be designed as a megavolt Lenard tube.

A third important member of the family of the early electron-beam tubes, direct descendants of the Crookes discharge tube, is the *cathode-ray tube*. It can be described as a low-voltage Lenard tube with a large fluorescent screen instead of the thin window at the far-off end of the tube, opposite the cathode. The electron beam impinging upon the screen produces a luminous spot which travels all over the screen as the

[6] E. E. Charlton and W. F. Westendrop, "A portable million-volt X-ray outfit for industrial laboratories," *Gen. Elec. Rev.*, vol. 44, pp. 652–661; December, 1914.

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[10] P. Lenard, "On cathode rays in gases at atmospheric pressure and in extreme vacuum," *Ann. der Phys.*, vol. 51, pp. 225–267; January 15, 1894.

beam is deflected. The deflection can be effected by a pair of condenserlike electrodes or by magnet coils arranged in close vicinity to the beam at the place where it emerges from the electron gun. By the deflection and luminous lines produced by the fluorescent spot one can study the character and mutual relation of voltages and currents energizing the deflecting electrodes.

The first tube of this kind was built by Ferdinand Braun in 1897.[11] For almost 30 years the Braun tube under the name of *oscilloscope* was used only in laboratories for qualitative study and relative measurements, mainly, in low-frequency technics.

However, as early as the first decade of this century Professor Boris Rosing of St. Petersburg,[12] Russia, and A. A. Campbell-Swinton in England[13] anticipated the feasibility of the application of the Braun tube in television. Rosing even succeeded in staging some initial experiments in that direction. Twenty-five years later, Zworykin and Farnsworth in this country brought these dreams to realization, Zworykin by designing his ingenious kinescope[14] and iconoscope[15] and Farnsworth by the not less ingenious dissector tube.[16]

Since the world-wide experimenting with radio-wave reflection from the Heaviside layer at the end of the 1920's, the cathode-ray tube was employed for measuring extremely short time intervals elapsed between the direct and reflected waves. This possibility permitted one to anticipate a variety of useful future applications in aviation, sea navigation and, perhaps, in highway and street traffic.

The modern cathode-ray tubes are a great improvement in practically every detail over the original Braun tube: the incandescent cathode (usually of the Wehnelt type) instead of the cold cathode; the electron gun for producing a narrow electron pencil, designed according to the rules of modern electron optics; superior qualities of the fluorescent screen replacing the old greenish willemite screen in television, etc. Cathode-ray tubes are now constructed in all sizes from the smallest "magic eye" in radio receiving sets to a tube 20 and even 24 inches in diameter. The variety of their application still increases steadily.

Mercury-Arc Rectifiers

The oldest electronic tube, or industrial tube par excellence, is the *mercury-arc rectifier*. It plays a very important role in modern industry whenever electric energy generated as alternating-current power is to be converted into direct-current form for operating direct-current railway and other heavy-duty motors with variable load; it is also very useful in industrial electrochemical processes.

The mercury-arc rectifier was invented by Cooper Hewitt[17] on the threshold of this century as a result of his experimenting with mercury-arc lamps, commercial manufacture of which was started by Cooper Hewitt and George Westinghouse in 1900. Production of the rectifiers[18] began in 1902.

It may be noted that for about twenty years before Cooper Hewitt's time, mercury-arc discharge in Crookes' tubes had been studied by several scientists. Thus, in 1882, Jamin and Meneuvrier[19] in France observed unidirectional flow of electric current from an anode to the mercury cathode (this was two years before the "Edison effect" was announced). Later on, similar work was done by a German professor, Arons.[20] But all these and similar scientific experiments were limited to laboratory demonstrations with no broad conclusions whatever. A systematic, experimental study of mercury-arc discharge and its practical applications was carried out in this country by Cooper Hewitt in co-operation with the Westinghouse Electric Company, and later on, also, by Weintraub,[21] Latour, and Steinmetz[22,23] of the General Electric Company.

The first rectifiers were made of glass and used for charging storage batteries, and also for feeding direct-current street-light arcs from alternating-current mains. But very soon the idea of a mercury steel-tank rectifier for converting power in larger quantity was conceived by Cooper Hewitt[24] (1908), and elaborated upon by himself, Frank Conrad and other workers in this field. The pioneer installation of this type of rectifier in this country was known to be made in 1913 at the Westinghouse Shadyside Works;[25] another followed it in 1914 for propelling a direct-current electric locomotive from an 11,000-volt single-phase overhead line of the New York, New Haven and Hartford Railroad.[26] In the latter project, two rectifier units fed four direct-current 240-horsepower motors at 600 volts.

[11] F. Braun, "On a method of demonstration and study of time curves of variable current," *Ann. der Phys.*, vol. 60, pp. 552–559; March 1, 1897.

[12] V. K. Zworykin, "Television," John Wiley and Sons, Inc., New York, N. Y., 1940, p. 256.

[13] A. A. Campbell-Swinton, "The possibilities of television," (A letter to the editor), *Nature*, vol. 78; p. 151; June 18, 1908; *Wireless World and Rad. Rev.*, vol. 14, pp. 51–56; April, 1924.

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[16] P. T. Farnsworth, "Television by electron image scanning," *Jour. Frank. Inst.*, vol. 218, pp. 411–444; October, 1934.

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[18] M. von Recklingshausen and P. H. Thomas, "Hewitt mercury lamp," *Trans. A.I.E.E.*, vol. 22, pp. 71–90; June 29, 1903.

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[20] L. Arons, "On mercury arc," *Ann. der Phys.*, vol. 47, pp. 767–771, November 15, 1892; vol. 58, pp. 73–95; May 1, 1896.

[21] E. Weintraub, "Investigation of the arc in metallic vapors in exhaust space," *Phil. Mag.*, vol. 7, pp. 95–124; February, 1904.

[22] C. P. Steinmetz, "The magnetic arc lamp," *Elec. World*, vol. 43, pp. 974–1175; June 24, 1904.

[23] C. P. Steinmetz, "Constant-current mercury arc rectifier," *Elec. World*, vol. 45, pp. 1174–1175; June 24, 1905.

[24] Cooper Hewitt, "Vapor converter," U. S. Patent 1,007,694; 1908–1911.

[25] O. K. Marti and H. Winograd, "Mercury Arc Power Rectifiers," McGraw-Hill Book Company, New York, N. Y., 1930, p. 8.

[26] W. S. Murray, "Main line electrification," *Trans. A.I.E.E.*, vol. 34, pp. 85–124; January 20, 1915.

It is known that a mercury-arc rectifier essentially consists of a glass or steel container having a small pool of mercury for the cathode and one or more carbon anodes (up to 24, in some rectifiers). Each of the anodes is energized by its own phase of the alternating-current power supply which is to be converted into direct-current power. The pool is connected to the load and, through it, to the common return of the alternating-current system. Unlike other thermionic tubes, the electrons necessary for carrying electric current through the mercury rectifier are obtained from a small bright "spot" which rapidly moves on the mercury-pool surface and forms the base of the mercury arc. An almost unlimited supply of electrons can be secured from this cathode without special provision for its heating. Hence, mercury-arc rectifiers are suitable for services requiring very high load current. In order to start the arc, the spot first must be struck, and then maintained during tube operation. This is accomplished by some kind of a "starter" and by one or more *auxiliary anodes* located close to the pool surface.

Glass rectifiers, because of hazards of mechanical breakage and of heat strains in their walls, and because of the involved glass-blowing work in making seals, are limited in permissible output by not over 500 amperes at about 600 volts rectified voltage. At lower current ratings, commonly required by broadcast transmitters, direct voltages of 10,000 volts and even higher can be realized. Modern steel tank rectifiers are built for 10,000 and even up to 16,000 amperes per unit. In this country mercury-pool rectifiers in glass containers are no longer manufactured, except for replacement services, but in Europe they are still in vogue.

A great advantage of the mercury-arc rectifiers over the rotary converters and over the other types of rectifiers is a very low internal-voltage drop, 20 to 30 volts, practically independent of load current. This renders rectifier efficiency very high, up to 98 per cent, and therefore the tube is suitable for applications where the load is highly variable, such as with cranes, streetcars, subways, main railroad lines, etc. Because of the unlimited supply of electrons, these tubes can be greatly overloaded for a short time without fatal effects, hence they are not damaged by short circuits on the line.

However, the internal short circuits caused by backfiring between the anodes and the cathode, or between two anodes always was and still is the main concern of the rectifier designers and for almost 30 years retarded its wide practical use in industry. The situation was aggravated by the reluctance of electrical engineers to part with their well-developed rotary converters in the same type of services. From the start it was known that a single backfiring does not put the rectifier out of commission, but a small amount of gas liberated by an overheated part prepares the way for another freak discharge, until finally the accumulation of spurious gas renders the tube inoperable. On the other hand, air could also diffuse into the tube through imperfect welds and gasket joints between the component parts of a steel tank.

Decisive steps in the direction of design improvement were originally made (1910) by Bela Schaefer of the Hartman and Braun Company, Frankfurt, Germany;[27,28] later on of the Brown and Boveri Company of the same country. A tank design was adapted radically departing from the shape of the glass rectifiers which had a side arm for each anode; reliable joints between parts were developed; and rectifiers in operation were kept continually exhausted, so that the uninvited gases could be removed on the spot. This scheme of evacuating the rectifiers in operation was greatly enhanced by the subsequent invention of mercury condensation pumps as mentioned before. The first two steel rectifiers in Europe were installed in a foundry near Frankfurt, Germany, in 1911.

During World War I, work on mercury rectifiers was discontinued everywhere in favor of other urgent problems, except in Germany where acute shortage in copper for building rotating machinery prompted rectifier development. So that, after the war, several prominent European concerns started manufacturing tank rectifiers, and large commercial installations began to emerge. This gave a new impulse to other countries which resumed their work in the same direction. This vast experience accompanied by scientific study of physical phenomena inside the rectifiers by several prominent industrial research workers finally gave a solid basis for designing modern steel-tank rectifiers. However, their application on a wide scale in this country did not start until after 1925. In 1930 the total power supplied by mercury rectifiers throughout the world rose to about 1.5 million kilowatts, while at the present time it has reached several million kilowatts in this country only.

An important item in the more recent development of mercury-arc rectifiers was the introduction of the control grid. It is interesting to note that Cooper Hewitt anticipated the possibility of controlling the rectifier current by a grid located in the path of the current. But grid control of a mercury arc by negative bias was explicitly suggested by a Langmuir patent in 1914.[29] However, probably because the patent was written around radio applications of the tube, the idea of grid control had not been seriously considered for mercury-arc rectifiers, until in 1924 Toulon proposed a new method of control by shifting the phase of the alternating voltage applied to the grid with respect to the anode voltage of the same frequency.[30] The Toulon method or its modifications permit an easy control of the direct-current rectifier output current and voltage,

[27] Bela Schaefer, "A new mercury-arc rectifier of large output," *Elek. Tech. Zeit.*, vol. 32, pp. 2–5; January 5, 1911.

[28] Bela Schaefer, "Large power mercury-vapor rectifiers with steel-containing vessels," *Elek. Tech. Zeit.*, vol. 33, pp. 1164–1168; November 7, 1912.

[29] I. Langmuir, "Electric discharge controlling device," U. S. Patent 1,289,823; 1914–1918.

[30] P. M. Toulon, "Current-regulating arrangement for rectifiers," U. S. Patent 1,654,949; 1923–1928.

without extraneous devices such as onload tap-changing transformers, or induction regulators. In addition to the advantages of efficient supplying power to a variable load, grid-control renders possible *inverted operation* of a rectifier, that is, inversion of the direct into alternating current without oscillating circuits. This is quite important for the realization in some near future of the dream of power transmission over long distance by means of very high direct voltages. Also, several other problems, can be solved by using grid control, such as feedback of the excess of power in direct-current traction into the alternating-current supply line, effective means of obtaining currents of variable frequency for induction furnaces, changing of the number of phases, or of the frequency of power supply, etc.

All advantages of the ordinary and of the grid-controlled mercury-arc rectifiers are inherent in the newest type of industrial electronic tubes, *the ignitron* (Fig. 2). In addition, this novel tube has some other useful features which contribute to its ever-growing popularity. The ignitron is also a "mercury-pool" tube. But the arc is started in it during each cycle by the *ignitor*. It is a short rod of a highly resistive refractory material with a pointed tip projecting into the mercury pool. When an electric (not electronic) current of a proper density is caused to flow from the ignitor to the pool during only a very short interval (about 100 microseconds) an arc is struck at the ignitor contact surface, and is almost instantaneously transferred to the anode. The electron current flows through the tube until the alternating anode voltage passes through its zero value. Then the arc can again be started by the ignitor, and so on. By means of phase shift in the timing circuit connected to the ignitor one may fire the arc at any desired point wthin the alternating-current cycle. In this manner it is possible to control both the number of cycles during which the ignitron operates, and the effective current per cycle. From this brief description it is clear that the ignitor performs two or even three duties at once; that of the keep-alive anodes (in starting the main arc during each cycle), of the control grid (in shifting the phase of initiation the anode current), and finally, of the starter in the mercury-pool rectifiers at the beginning of its work.

There are several advantages of single-anode mercury tubes, such as the ignitron. Indeed, it lends itself to large-scale production, since the component parts of a simple cylindrical structure can be readily welded together by modern methods; the necessary insulation between the tube parts can be of the rugged and reliable kovar-to-glass seal type; better joints, better seals, and better outgassing of parts permit making of all-metal tubes of the sealed-off type, even at higher ratings; the individual tubes can be conveniently handled at the factory and in the field; backfiring in the tube can be reduced to its physical minimum because there is no ever present keep-alive arc. Finally, single-anode tubes can be operated in reverse-parallel connection, realizing a perfectly controlled single-pole double-throw instantaneous switch, the scheme widely used in resistance welding which is perhaps the most important electronically controlled process in modern industry. Resistance welding has been up to the recent time the main application of the ignitron, and many units of welding equipment have been installed during the last 7 or 8 years for numerous consumers all over the coun-

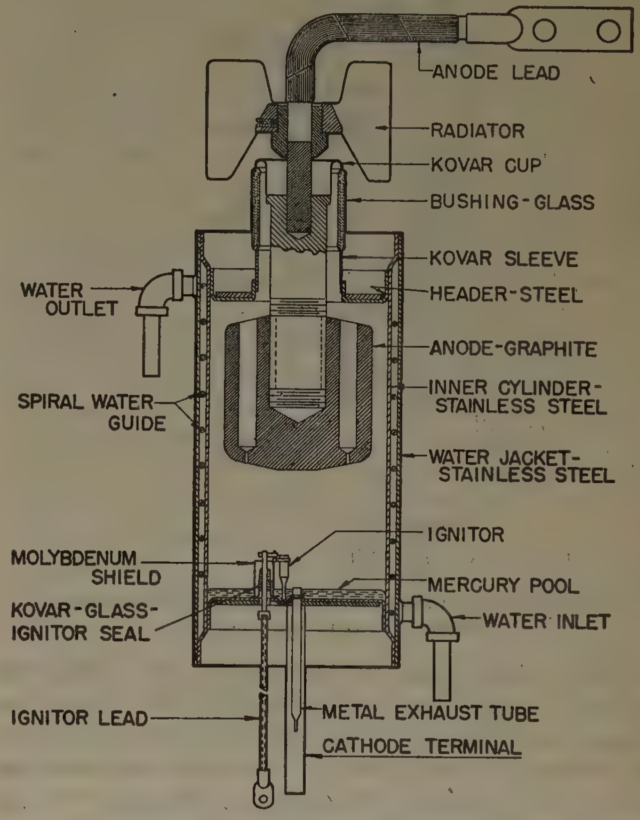

Fig. 2—Size D ignitron for 2400 kilovolt-amperes maximum demand and 14,400 amperes maximum peak current at 250 volts.

try. However, there is no reason not to use the ignitron in other applications. In fact, a number of sets with a total power amounting to about 2½ million kilowatts has been installed since 1940 in the electrochemical industry for production of aluminum, magnesium, and other metals, in which ignitrons serve as precision controlled rectifiers. Ignitrons can also be designed for sufficiently high voltages to be used for supplying power to large transmitting radio sets.

The ignitron was invented by Slepian and Ludwig of the Westinghouse Electric and Manufacturing Company,[31] and has been used commercially since 1937. Modern ignitrons are almost exclusively of the all-metal type. At the present time there are several standard types in manufacture, ranging from 1700 to 27,000 amperes peak and up to 900 amperes average anode current.

In quite recent times another type of a single-anode

[31] J. Slepian and L. R. Ludwig, "New method of starting an arc," *Elec. Eng.*, vol. 52, pp. 605–608; September, 1933.

tube was developed by the Allis-Chalmers Company, the so-called *excitron*.[32] This is an all-metal mercury-pool tube with a control grid. It possesses all the advantages of a single-anode tube, just outlined. The difference between the excitron and ignitron is in the electronic mechanism of starting and controlling the current dur-

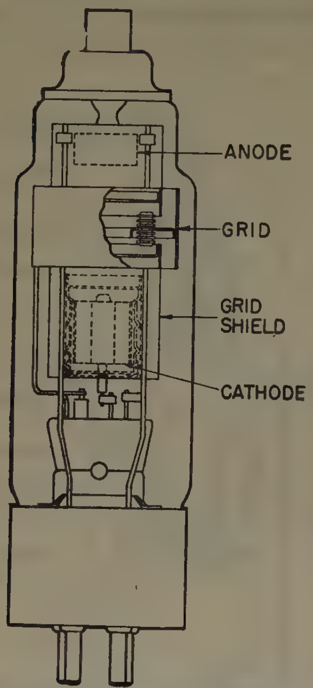

Fig. 3—WL-672 thyratron for 1500 volts, 2.5 average and 30 amperes peak anode current.

ing each cycle, that is, the control-grid versus the ignitor. It seems that the ignitor makes the tube structure simpler as it eliminates the keep-alive anodes and the necessity of having another device for initiating the arc at the beginning of operation. However, the designers claim that the excitron proved to be satisfactory in service.

Another very important member of the family of mercury vapor or gas tubes is *the thyratron* (Fig. 3). In its simplest form it is a gas or mercury-filled triode with a filamentary cathode. Although all early radio receiving triodes fall under this definition, the industrial application of the thyratron in the modern sense of the word was first suggested in 1928–1929 by Hull[33] of the General Electric Company. Actually, the basic principle of its operation was anticipated much earlier.[29]

The thyratron has a thermionic cathode, a graphite or metal anode, and a control grid surrounding the anode. In modern tubes there usually are two grids: one for controlling the beginning of the discharge, the other for shielding the cathode from the anode electric field. The second grid also performs several other functions tending to improve the effect of the grid control. The thyratrons are usually filled with mercury vapor by placing a drop of pure mercury inside the tube after its exhaust. Some of the modern thyratrons are filled with one of the heavy monatomic gases, xenon or krypton, rendering the tube operation more nearly independent of the ambient temperature. The cathodes of mercury tubes are of the oxide type, directly or indirectly heated.

There are several standard types of thyratrons assembled in glass envelopes, but attempts are being made to design all-metal tubes along the same lines as the ignitrons are built.

The thyratron is an indispensable tube in modern industry. Similar to the larger mercury tubes (ignitron, excitron) it can be used alone for precise controlling of current and voltage, when power demand is not too high. It is also very useful in regulation service in the circuits designed to keep temperature, motor speed, generator voltage, etc., within the prescribed narrow limits. In circuits designed for counting manufactured goods or other objects, rejecting defective pieces, etc., which utilize sensitive photocells, the thyratron excited by the photocell is a very convenient tool to operate necessary mechanisms. Finally, the thyratron offers a beautiful means for the precise control of firing ignitrons or grid-controlled mercury-pool tubes. The thyratron is a true and simple *electron relay*, the name by which the first radio tubes were sometimes called.

The simplest member of mercury tubes is *the phanotron*. This is a mercury-vapor-filled diode or rectifier. It

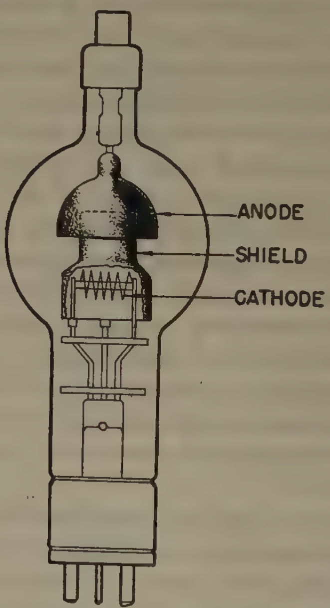

Fig. 4—869-B phanotron for 15,000-volt peak inverse voltage and 5 amperes average current.

consists of a thermionic filamentary (or indirectly heated) cathode and a graphite anode (Fig. 4). Several types of phanotrons, all of the sealed-off variety with glass envelopes, are well known in radio application; in the field of power supply to radio sets they have made the early high-vacuum rectifiers practically obsolete, because of their great efficiency and higher current ratings. The only limitation of the phanotron is the

[32] H. Winograd, "Development of excitron-type rectifiers," A.I.E.E Technical Paper No. 44–78; March, 1944.

[33] A. Hull, "Gas-filled thermionic tube," *Trans. A.I.E.E.*, vol. 47, pp. 753–767; July, 1928; "Hot cathode thyratrons," *Gen. Elec. Rev.*, vol. 32, pp. 213–223; April, 1929.

permissible direct voltage which cannot conveniently exceed 10 or 15 kilovolts without eventually firing back. Since structurally a phanotron is a thyratron with the grid, this type appeared practically simultaneously with the thyratrons, that is, at the end of the 1920's.

The cold-cathode thyratron filled with argon or neon was originally known as "grid-glow tube."[34] Its application preceded that of the hot-cathode thyratron by several years. It is still used in services with long stand-by periods, as it does not consume power for heating the cathode.

High-Vacuum Rectifiers

In some previous as well as in the following Sections reference is made to an event which has played an outstanding, although indirect, role in the development of all types of electronic tubes. This was a great improvement in vacuum technics as the result of the invention of the molecular[35] pump by Gaede (1913) and of the *mercury diffusion* and *condensation pump* by Gaede (1915)[36] and Langmuire (1916).[37,38] With the new pumps it was possible to exhaust tubes to a much greater degree of vacuum then previously. Vacua of at least 10^{-6} millimeter of mercury became easily attainable; this was essential with tubes designed for high-voltage operation as only in high vacuum could pure electron currents unimpeded by the presence of gas ions be established.

The first fruit of the improved vacuum technics was the improved high-vacuum X-ray tube followed shortly by high vacuum rectifiers[39] also known as *kenotrons* (1915). The kenotron is a clean-cut diode with a filamentary cathode, usually made of pure tungsten. The first application of high-vacuum rectifiers was supplying rectified direct voltages to X-ray tubes from high-voltage transformers. In this service the kenotron replaced the old mechanical "valves".

With the improvement of radio transmitters the original motor-generator sets used for supplying direct operating voltage to the oscillator tubes were gradually replaced by alternating-current power-supply sets employing kenotrons. This evolution has not required the development of the new types of tubes as practically every triode could be converted into a rectifier simply by omitting the grid. However, the inherent drawbacks of high-vacuum rectifiers soon came to light; frequently they had insufficient maximum emission current and their internal voltage drop was too great. Thus, toward the end of the 1920's moderately successful attempts were made to adapt mercury-pool rectifiers for radio sets; but very soon in this country kenotrons lost their place to phanotrons for high-duty services. The kenotron still has a very important application in connection with supplying direct-current power, whenever emphasis is placed on high voltages rather than on high currents; such as is the case with X-ray tubes, precipitrons, etc.

High-Frequency Tubes

Up to the most recent time the classification, *industrial* versus *radio* tubes, coincided with the tube division into *gas-filled* versus *high-vacuum tubes*. It was to a certain degree justified, since, by virtue of the physical phenomena in the conventional gas-filled tubes, they could be used only in circuits of low or industrial frequencies (25 or 60 cycles per second); on the other hand, high-frequency radio applications required tubes with as good vacuum as can be established by the modern vacuum technics. However, at the present time, even discounting therapeutic application of high-frequency oscillations, there are industrial installations in which high-frequency or "radio" tubes are employed for induction and dielectric heating of parts and materials in a variety of manufacturing processes.

Nevertheless, up to the present time the development of high-frequency tubes was always intimately connected with the progress of the radio art; this may be modified in the future, as no intricate characteristics are required from industrial tubes but power and efficiency.

The first vacuum tube ever used in high-frequency circuits was built in 1892 by Zehnder[40] for demonstrating to large audiences Hertzian waves, then recently discovered. The Zehnder tube was a small gas-filled tube in which gas discharge was triggered by high-frequency oscillations. The first tube developed for practical radio applications was the noted Fleming valve (1904),[41] a diode detector based on the phenomenon of unidirectional conduction of electric current, recorded by Edison twenty years earlier,[42] while experimenting with incandescent lamps. Simultaneously, in Germany another diode detector with a straight *oxide-coated* filament and a cylindrical aluminum anode was produced by Wehnelt,[43] the inventor of oxide-coated cathodes. Then, in 1908, the first three-electrode tubes appeared; this was the epoch-making de Forest's *audion*.[44,45] About the

[34] D. D. Knowles and S. P. Sashoff, "Grid controlled glow and arc discharge tube," *Electronics*, vol. 1, pp. 182–185; July, 1930.

[35] W. Gaede, "The molecular air pump," *Ann. der Phys.*, vol. 41, pp. 337–380; June, 1913.

[36] W. Gaede, "Gas diffusion through mercury vapor at low pressure and a diffusion pump," *Ann. der Phys.*, vol. 46, pp. 357–392; February, 1915.

[37] I. Langmuir, "The condensation pump," *Gen. Elec. Rev.*, vol. 19, pp. 1060–1071; December, 1916.

[38] I. Langmuir, "The condensation pump," *Jour. Frank. Inst.*, vol. 182, pp. 719–743; December, 1916.

[39] S. Dushman, "New device for rectifying high tension alternating-current," *Electrician*, vol. 75, pp. 276–277; May, 1915; *Gen. Elec. Rev.*, vol. 18, pp. 156–167; March, 1915.

[40] L. Zender, "Radiation of electric force" *Ann. der Phys.*, vol. 47, pp. 77–92; September 1, 1892.

[41] J. A. Fleming, "Thermionic valve," British Patent 24,850; November 16, 1904.

[42] T. A. Edison, "Electrical indicator," U. S. Patent 307,301; October, 1884.

[43] A. Wehnelt, "An electric valve," *Ann. der Phys.*, vol. 19, pp. 138–156; January, 1906; *Phys. Zeit.*, vol. 5, pp. 680–681; October 20, 1904 (preliminary information).

[44] Lee de Forest, "Space telegraphy," U. S. Patent 879,532; January, 1907–February, 1908.

[45] Lee de Forest, "The audion-detector and amplifier," Proc. I.R.E. vol. 2, pp. 15–30; March, 1914.

same time, but later than de Forest, several other inventors in different countries proposed similar tubes. One may note that the effect of the grid on electrostatic field has been known to scientists from the fundamental works of Maxwell and Rieman.

All early radio tubes were "soft" tubes. In fact, at that time there was no means for establishing what we

Fig. 5—320-A—Western electric 250-kilowatt tube.

now call high vacuum; on the other hand, for almost ten years, the physical phenomena in vacuum tubes in operation, especially the role of the residual gas, were not quite understood. Gas was even considered as an essential factor in proper tube performance. Moreover, mercury-arc tubes for reception and generation of radio waves were proposed by several inventors. The importance of high vacuum in radio tubes was not realized until theoretical work by Langmuir in this country and Schottky in Europe had been made known.[46,47] This coincided with a considerable improvement in vacuum technics brought about by Langmuir and Gaede mercury pumps capable of establishing the highest necessary vacua.

A direct result of better vacuum pumps was designing and construction of triodes which could be operated at higher voltages and hence were able to generate or to amplify high-frequency output up to several hundred watts. This progress in tube design, as it is widely known, was directly responsible for the inauguration of the most important branch of engineering art of our time, radio broadcasting (1920). However, soon the output from the individual tubes designed after the pattern of the early receiving tubes enclosed in glass envelopes reached its practical limit of 1 or 2 kilowatts; at higher ratings the tubes would turn out bulky and difficult to manufacture. Then, the invention by Housekeeper of the glass-to-copper seals, in 1922, gave a new impetus to radio-tube development, since water-cooled anodes could be constructed for much higher ratings. At once, the high-frequency output from a single tube rose to 10 and 20 kilowatts, and nothing was in the way of designing much larger modern tubes. In Europe, indeed, prior to this war, all leading manufacturers produced tubes with 350- and even 400-kilowatt output. In this country, however, because of the restriction imposed by the Federal Communications Commission on the output from broadcast transmitters, tubes for more than 100 kilowatts output have not been developed, although for a long time the leading role in development of large tubes belonged to this country. Only recently, a 250-kilowatt tube was announced by the Western Electric Company (Fig. 5).

The emergency of the last few years compelled manufacturers in many branches of industry to turn to "electronic processes". Among these applications induction and dielectric heating of manufactured parts and materials with a variety of purpose became very popular; high frequency or radio tubes were required in large numbers for these services, and proved to be a great success. It is enough to mention that in several (five or

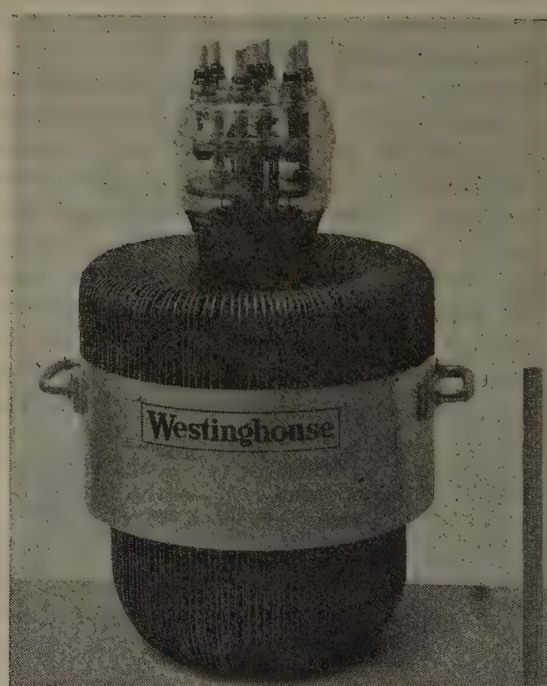

Fig. 6—WL-895-R modern 100-kilowatt maximum rating tube for radio and industrial applications.

[46] I. Langmuir, "The pure electron discharge," *Phys. Rev.*, vol. 2, pp. 450–486; December, 1913.

[47] W. Schottky, "The effect of space charge on thermionic currents in high vacua," *Phys. Zeit.*, vol. 15, pp. 526–528; April, 1914; also, pp. 624–630; May, 1914.

six) installations for tin-reflowing, the total high-frequency power utilized is greater than the total nominal power of all broadcast transmitters in this country. The 100-kilowatt tube employed in these projects is of a modern design and was originally intended only for broadcast service; it is shown in Fig. 6. Obviously, if in the future there will be a sufficient demand, tubes of greater ratings can be designed. However, one may anticipate that 500 kilowatts is perhaps the ceiling for practical rating of individual sealed-off tubes; above this figure one may foresee that the cost of tubes will be out of proportion to their advantages because of increased difficulties in design and in manufacturing the tube.

It looks as though in this case industry may turn to the *demountable* tubes; these can be assembled and taken apart for repairs at the place of their use, like engines. The main objection to this type is that they must be continually exhausted in operation, hence they require a better-trained personnel. But the continually pumped mercury-tank rectifiers may serve as a rather encouraging example.

The demountable tubes are not new. Since 1923, the French Navy had in service a number of 10- and 30-kilowatt demountable tubes, designed by Holweck. During the decade preceding this war, because of the invention of the new and improved oil-condensation pump by Burch in England, a few demountable tubes of larger size were in operation throughout Europe in radio; but mainly they became popular in the metallurgical industry for melting alloys. In this country the application of demountable tubes is thus far limited only to a few scientific projects, such as cyclotrons, megavolt X-ray tubes, etc.[48]

While touching upon the types of high-frequency tubes one may note that *forced air-cooling* can be adapted practically to every water-cooled type of tube by soldering or brazing the tube in a specially designed multifinned cooler. Air-cooling represents advantages in those cases when water is not to be wasted; or when one does not wish to go to the expense of building a complicated plumbing system for distilling and recirculating water; or, simply, when the tubes are to be installed in an unheated room, in which ambient temperature may sink below 10 degrees centigrade.

Air-cooling was introduced into practice about eight years ago and since then has become quite popular. Fig. 6 shows the 895 tube in an air-cooler. Made of copper, this cooler weighs about 250 pounds. This, of course, is objectionable from the viewpoint of handling the tube in the factory, in transportation, and in the field. Therefore, one may expect that the time is not remote when aluminum will replace copper in these coolers. For the realization of this, one needs a simple method of establishing a reliable bond between the aluminum cooler and copper anode.

From the viewpoint of the internal structure and the number of elements for controlling the electron current, large or transmitting tubes are of simpler types than small receiving tubes. Just a glance through an RCA Handbook for receiving tubes persuades one that their design is limited only by the type of service required and by the imagination of the designer, as there are apparently no insurmountable manufacturing difficulties in the way of the realization of the most complicated structure. Such designs as that of "octode converters" having 6 grids (7A8), or of the "diode-triode-power-amplifier-pentode" with two cathodes, three anodes, and four grids (1D8-GT) are unthinkable in the larger tubes. Practically, all transmitting tubes with external anodes, up to recent times, were of the triode type. Radiation-cooled types assembled in glass envelopes can be more easily built and are built as screen-grid tubes or tetrodes, while the smaller members of this family are sometimes designed as pentodes.

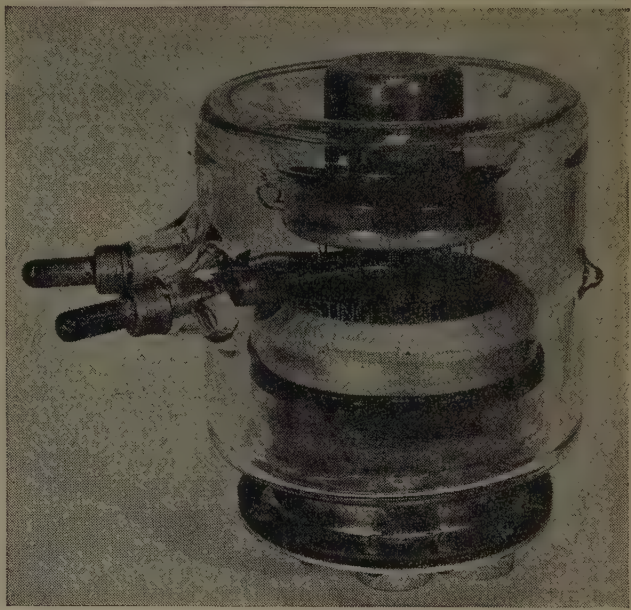

Fig. 7—WL-530 ultra-high-frequency triode for special applications. The first water-cooled tube designed with heavy self-supporting bird-cage thoriated tungsten filament and 100 per cent utilization of the anode surface.

With the advent of television, frequency modulation, and some other special services, a demand arose within the last ten years for *ultra-high frequency tubes*. In response, several triode amplifiers became available for these services capable of generating power of several kilowatts at required frequencies from 40 to 100 megacycles. Such are the 880, 889, 530 types and several others. These tubes are designed along the same general lines as the conventional triode, but they are of a short squat structure with inverted copper-to-glass seals (Fig. 7), or with kovar skirts brazed to copper anodes in order to reduce the total length of the tube; also, molded-glass

[48] I. E. Mouromtseff, H. J. Dailey, and L. C. Werner, "Review of demountable versus sealed-off power tubes," Proc. I.R.E., vol. 32, pp. 653–664; November, 1944.

dishes from which all internal parts are supported are characteristic of these tubes. All these features are necessary for the reduction of the tube's internal inductance and interelectrode capacitance which is the main limiting factor in amplifier operation in the designed ultra-high-frequency band. It is quite possible that tetrodes of a good mechanical design will give a more satisfactory performance in these services.

However, with the existing trend to extend television and frequency modulation into the bands of higher and higher frequencies, it is certain that both the triodes and tetrodes of conventional designs, even if trimmed to the utmost with respect to the interelectrode capacitance and internal tube inductances, will not satisfy the new demands on account of the transit-time limitation. One has to look for a solution with the tubes in which the oscillating circuit and the electronic mechanism of the tube are designed together as integral parts of the same device. Two types of such devices have been known for several years: the magnetron and velocity-variation tube.

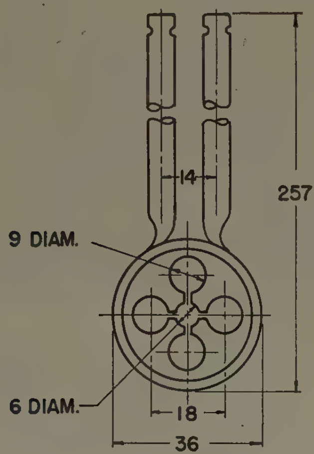

Fig. 8—Multiple water-cooled magnetron of Russian design for very high frequencies.

The *magnetron* is quite an important member of the vacuum-tube family. It was invented by Hull in 1921 as a power inverter, or power-controlling device. In 1928, two Japanese professors, Yagi and Okabe, found that a magnetron with the anode split into two or more segments is capable of producing oscillations of extremely high frequencies. Since that time vast work has been done by physicists and radio specialists all over the world. In 1940, a novel type of magnetron was described in the Russian technical press and republished in this country.[49] This tube consists of several individual magnetrons of small diameter (Fig. 8), with their centers arranged in a circle; the whole array is machined in a solid block of copper. The most important innovation is that, instead of the usual external circuit, a cylindrical "cavity resonator" is coupled to each magnetron, and all are coupled together through a common central cavity. The authors reported that with this tube they were able to generate 300 watts at a 9-centimeter wavelength. In order to appreciate this improvement one may mention that, when Kilgore of East Pittsburgh reported in 1932 1 watt output from his, then new, magnetron at about the same frequency, it was considered enormous; many interesting feats in transmission of radio beams could be demonstrated with this tube. Previously, even a small fraction of a watt at this frequency was considered satisfactory.[50]

Another "unusual" type of tube of the future is the *klystron* which belongs to the family of electron beam and *velocity-variation* tubes. Attempts to harness a narrow beam of electrons to generate oscillations were made more than 40 years ago by Cooper Hewitt, and then by Vreeland in this country. The latter even succeeded in constructing a practical oscillator with a mercury-arc tube generating 500 cycles per second for laboratory measurements.[51] Then, as early as 1907, an electron-beam tube, in which a magnetically controlled beam swung back and forth between two anodes in high vacuum, was proposed as a radio detector by von Lieben of Vienna.[52] In more recent times, when radio engineers became ultra-high-frequency-minded, a number of beam oscillators has been proposed, based largely on a rotating or swinging back and forth beam in a cathode-ray tube with multiple anodes.

The first electron beam in which the initially uniform electron beam is converted into a succession of electron clusters by means of velocity variation was described by the Heils, 1935.[53] However, not all early beam oscillators were successful in practical applications, because they were forced to deliver power into conventional high-frequency circuits of low impedance, which did not match the inherently very high internal impedance of the beam tubes. It was not until Hansen had studied[54] and popularized "cavity resonators" that electron-beam tubes could be designed with an acceptable efficiency and output, even at extremely high frequencies. The first, and a very good representative of the velocity-variation beam tubes with cavity resonators for oscillating circuits, was the klystron developed by the Varian brothers,[55] in 1939. A variety of applications of the klystron may be anticipated in postwar electronics.

[49] N. F. Alexeev and D. D. Maliaroff, "Generation of oscillations with a magnetron in the centimeter band," Proc. I.R.E., vol. 32, pp. pp. 136–139; March, 1944.

[50] A. G. Clavier, "Production and utilization of micro-waves," *Elec. Commun.*, vol. 12, pp. 3–11; July, 1933.

[51] H. K. Vreeland, "A sine-wave oscillator of the organ pipe type." *Phys. Rev.*, vol. 27, pp. 286–293; October, 1908.

[52] V. R. von Lieben, German Patent 179,806; 1906.

[53] A. Arseniewa Heil and O. Heil, "New method of generating short continuous waves of high intensity," *Zeit. Phys.*, vol. 95, pp. 752–762; July, 1935.

[54] W. W. Hansen, "On the resonant frequency of closed concentric lines," *Jour. Appl. Phys.*, vol. 10, pp. 38–45; January, 1939.

[55] R. H. Varian and S. H. Varian, "A high frequency oscillator and amplifier," *Jour. Appl. Phys.*, vol. 10, pp. 321–327; May, 1939.

Phototubes

Many industrial or nonradio applications of electronic tubes of all kinds are greatly enhanced, or even made possible, by the use of *photocells*. Other tubes, thyratrons or high-vacuum amplifiers, actuated by minute phototube currents and voltages, are used to operate all kinds of mechanisms and electronic circuits.

The phototube is the only modern electronic tube which cannot claim direct descent from the Crookes discharge tube or from the incandescent lamp, although later in its career its design was benefited by the technics and theories developed in connection with other electronic tubes. Photoeffect was first observed in a wet cell and recorded by Becquerel in 1839 with no deductions whatever. Then it was observed under different circumstances by Hertz, during his epoch-making experiments with electromagnetic waves, in 1888. Immediately, Wilhelm Hallwachs took notice of this and carried out a study of photoelectricity, which was followed by the work of several other scientists, like Righi and the noted physicists, Elster and Geitel. The first photocell useful in scientific measurements consisting of copper oxide on copper was built by Hallwachs, while the first alkali cell almost in its modern form was introduced by Elster and Geitel, in 1912.

The applications of phototubes in modern electronics in a variety of control and regulation devices are too numerous even to attempt to list them. However, one may specifically remember one outstanding application of photosensitive films: this is in television pickup tubes, iconoscope, image dissector, etc., in which the mosaic consists of a multitude of tiny photocells.

Some Notes on the Design of Electron Guns*

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Summary—A method is outlined for the design of electron guns based on the simple theory first published by J. R. Pierce. This method assumes that the electrons are moving in a beam according to a known solution of the space-charge equation, and requires that electrodes exterior to the region of space charge be shaped so as to match the boundary conditions at the edge of the beam. An electrolytic tank method is used to obtain solutions for cases which are not amenable to direct calculation. Attention is given to some of the complications ignored by the simple theory and to some of the practical difficulties which are encountered in constructing guns according to these principles. An experimental check on the theory is described, together with some information as to the actual current distribution in a beam produced by a gun based on this design procedure.

Introduction

THE PROBLEM to be considered in the present paper is the practical design of electron guns to give reasonably high currents and high current densities without the sacrifices in beam current which are normally accepted in cathode-ray-tube guns. The first part of the paper consists of an elaboration of the simple theory as first published by Pierce.[1] Attention will then be given to some of the practical difficulties which are encountered when one attempts to build electron guns according to these principles, and an experimental check on the theory will be described.

Fundamental Theory

Following the method outlined by Pierce,[1] we will start by assuming that the electrons are moving in a beam according to known solutions of the space-charge equation. Electrodes exterior to the beam are shaped so that boundary conditions are consistent with the assumed motion. This method results in a simple mathematical description of the fields inside and outside of the beam when the beam is actually present in the electrode system. It completely avoids any separate consideration of the diverging space-charge effect in the beam in the absence of surrounding electrodes, and of the converging effect of the electrode system in the absence of the beam.

The first problem is that of showing that a uniform rectilinear electron flow, according to the known space-charge equations, is theoretically possible in limited regions with abrupt boundaries. For example, consider the flow of electrons from a plane cathode to a parallel plane anode. As long as these planes are infinite in extent, and conditions of complete space charge are assumed, the potential distribution is completely defined and follows the well-known Child equation.[2] If, however, it is desired to have the condition of space charge flow over a restricted area, then one must satisfy certain boundary conditions at the edge of the beam. Of course, in all practical electronic devices, the electron flow does occur in limited regions, but there usually exists a border region in which the electron flow is neither uniform nor rectilinear. We are now concerned with the problem of abruptly terminating the region of rectilinear flow. A moment's reflection will show that two conditions must be met in the absence of a transition region or of sheets of surface charge. In the first place, the potential must be continuous across the boundary; that is, the

* Decimal classification: R388. Original manuscript received by the Institute, October 5, 1944. Presented, National Electronics Conference, Chicago, Ill., October 6, 1944 (the Chicago Section of The Institute of Radio Engineers was one of the sponsors of the National Electronics Conference).

† Bell Telephone Laboratories, Inc., New York, N. Y.

[1] J. R. Pierce, "Rectilinear electron flow in beams," *Jour. Appl. Phys.*, vol. 2, pp. 548–554; August, 1940.

[2] C. D. Child, "Discharge from hot CaO," *Phys. Rev.*, vol. 32, pp. 492–511; May, 1911.

potential just outside the beam must be everywhere identical with the potential just inside the beam. The potential inside the beam is, of course, specified by Child's equation, or, in the more general case, by a solution of Poisson's equation, while the potential outside the beam must satisfy the Laplace equation. The second condition is that the potential gradient normal to the beam must be zero along the boundary surface; otherwise, the electron flow could not remain rectilinear. If a solution for a potential distribution exterior to the beam can be found which satisfies these two conditions along the boundary, then it is possible to have an abrupt boundary to the beam. Pierce has shown that this is indeed theoretically possible, and he has furthermore calculated the required potential distributions outside the beam for several special cases. To achieve these potential distributions, it is necessary only to enclose the region surrounding the beam by metal surfaces which are shaped to conform with the computed equipotential surfaces, and maintain these metal surfaces at the indicated potential.

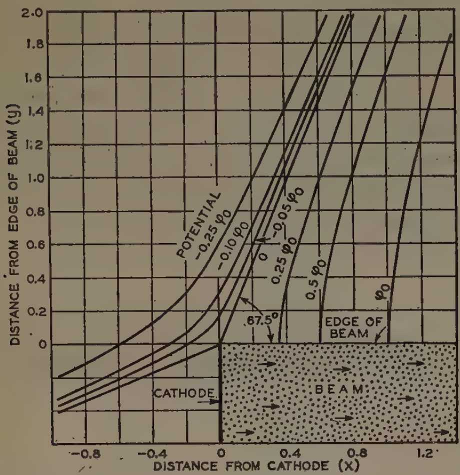

Fig. 1—Equipotential surfaces for parallel rectilinear electron flow with plane boundaries.

Suppose, for example, that we consider the case of parallel flow with plane boundaries, in which the electrons entering the region come from a cathode forming one boundary and giving space-charge-limited emission. A plot of the calculated equipotential surfaces is shown in Fig. 1. All of the units are arbitrary, as the shapes of the equipotentials are independent of the absolute magnitude of the potentials involved and of the units in which distance is measured. Potentials are indicated in terms of an arbitrary potential ϕ assigned to one equipotential as measured from the cathode. It will be seen that the zero potential surface is a plane which makes an angle of 67.5 degrees with the normal to the cathode at its edge. Two examples of the way in which these principles might be applied are shown in Fig. 2. As shown on Fig. 2(A), a zero-potential electrode and a positive-potential electrode may be combined to give a parallel beam of electrons if a grid is used to permit the electrons to pass through the positive electrode. In Fig. 2(B), both negative and positive electrodes are used and the beam passes through a slit in the second electrode. When the width of such a slit is considerably less than the cathode-anode spacing, it has only a small effect on the space-charge conditions in the vicinity of the cathode, but it will have a lens action. If the region to the right of the anode is field free, the beam will diverge as shown.

Solutions by the Electrolytic-Tank Method

In the practical case, we frequently require more complicated configurations which become progressively more difficult to compute. An experimental approach to the problem is required. As is well known, an electrolytic tank can be used to solve problems of potential distribution in the absence of space charge. The only problem is that of simulating the edge of the beam. Pierce has suggested that this be done by means of an insulating strip. As no current can enter this strip from the electrolyte, the potential gradient within the electrolyte must of necessity be zero at its surface. With the condition of zero field normal to the beam boundary so easily disposed of, the problem of finding suitable electrode shapes is merely that of adjusting the shapes and positions of the electrodes in the tank until the potential along the insulating strip varies as the appropriate function of distance corresponding to the assumed space-charge conditions in the beam. It should be emphasized that in this method the region represented in the tank is only that portion of space external to the beam. The space-charge region is carefully excluded by the insulating strip.

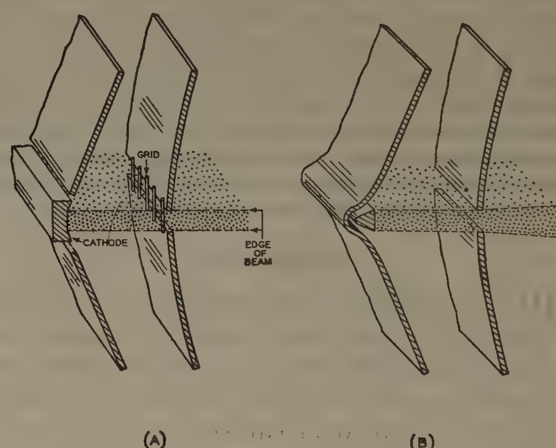

Fig. 2—Illustrations of the way in which bounding surfaces may be constructed to conform with the equipotential surfaces shown in Fig. 1.

Let us consider how this method can be applied in the design of electrodes to give parallel electron flow with cylindrical boundaries. Rather than attempting to represent the entire beam, it is convenient to work with only a thin wedge-shaped body of electrolyte formed by planes cutting through the axis of symmetry as

originally suggested by Manifold and Nicoll.[3] This procedure is possible in all cases involving axial symmetry. A simple tank construction is shown in Fig. 3. The bottom is a tilted plane of nonconducting material. The thin edge of the wedge of electrolyte is the axis of symmetry corresponding to the axis of the cylindrical beam. Suitable electrodes to establish symmetrical equipotentials would be portions of figures of revolutions about this axis. When the angle of the wedge is small, these can be replaced by singly curved electrodes bent from flat sheets. The edge of the beam is represented by the insulating strip, which in this case is parallel to the thin edge of the wedge and spaced from it a distance corresponding to the radius of the electron beam. A calibrated potentiometer is used to measure the potentials along the insulating strip, and the electrodes are moved

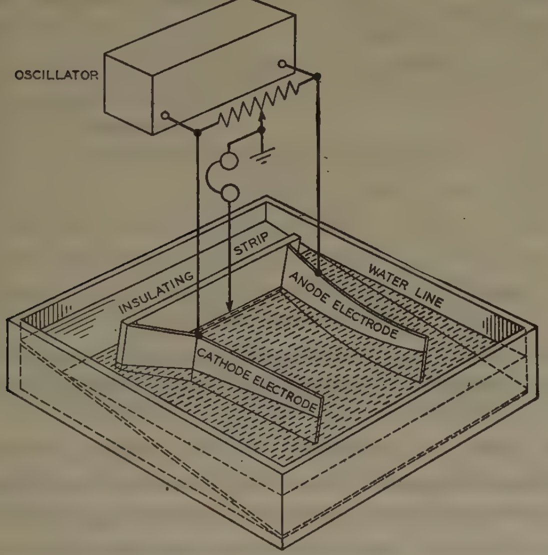

Fig. 3—Electrolytic-tank construction for problems possessing axial symmetry.

about and changed in shape until the desired potential distribution is obtained.

Equipotential surfaces obtained in this way are shown in Fig. 4. As before, the zero potential surface makes an angle of 67.5 degrees with the normal to the cathode. In fact, it can be shown that this is true under all conditions. These surfaces are, of course, only approximately correct. Although there exists but one unique set of equipotential surfaces which exactly match the boundary conditions, it is a fortunate fact that a relatively large number of electrode shapes can be found which produce a good approximation. This allows one to make a certain amount of adjustment of electrode shapes to meet the physical limitations of tube-construction methods.

While only two examples of rectilinear flow between parallel plane electrodes have been considered, it should

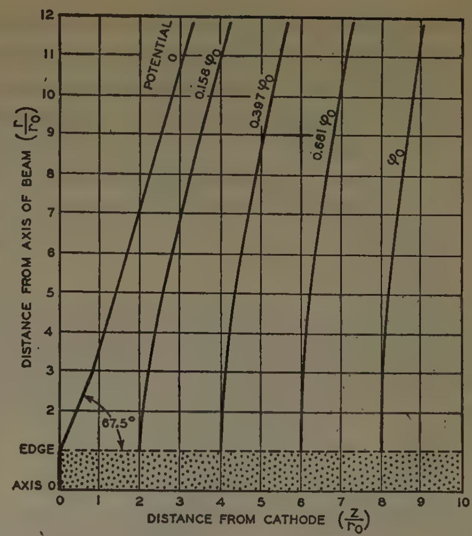

Fig. 4—Equipotential surfaces for parallel rectilinear electron flow with cylindrical boundaries.

be realized that the principles are not restricted to these two examples. Any form of bounding surface can be treated in the same way. The more general conditions of space-charge flow, for which the potential distributions are known,[4] can be treated in an identical fashion.

The same principles can obviously be applied in the case of radial flow between cylinders and spheres. These

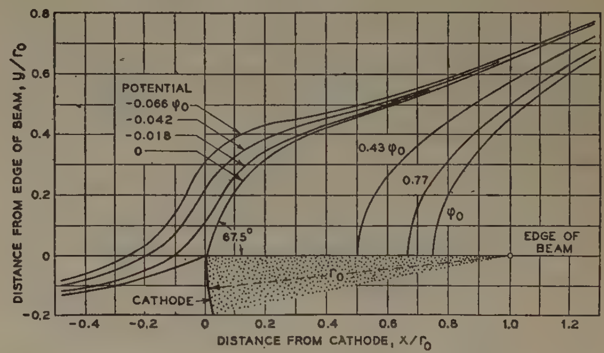

Fig. 5—Equipotential surfaces for radial rectilinear electron flow between segments of cylinders.

cases are of considerable practical interest, as they permit the concentration of the electron emission from a cathode either into parallel beams of high current densities or into converging beams.

The equipotential surfaces for radial rectilinear electron flow between segments of coaxial cylinders can be calculated by an approximate method. These are shown in Fig. 5. Fig. 6 shows a line-focus electron gun based on such equipotentials. Electrons leaving the cathode move along radii until they approach the anode. In passing through the slit in the anode, the beam suffers a diverging action which may be calculated from Davisson's

[3] M. Bowman Manifold and F. H. Nicoll, "Electrolytic field plotting-trough for circular symmetric systems," *Nature*, vol. 142, p. 39; July 2, 1938.

[4] C. E. Fay, A. L. Samuel, and W. Shockley, "On the theory of space charge between parallel plane electrodes," *Bell. Sys. Tech. Jour.*, vol. 17, pp. 49–79; January, 1938.

equation[5] which gives the focal length of such a lens as $f=2\phi/E_2-E_1$ where ϕ is the potential at the slit and E_1 and E_2 are the potential gradients which would exist on each side in the absence of the slit. The value of E_1

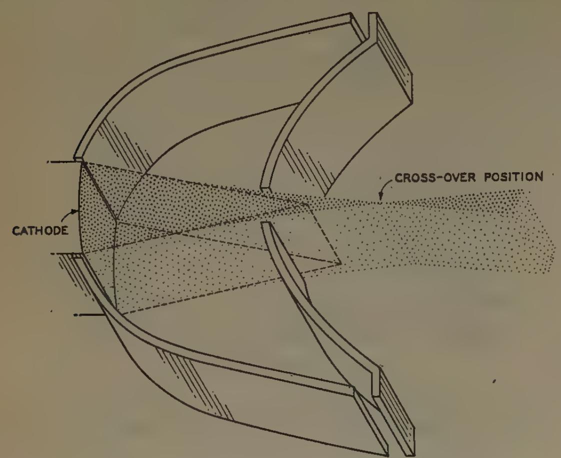

Fig. 6—A gun structure based on radial electron flow between segments of cylinders.

is, of course, that given by the space-charge equation in the gun region. The gradient on the other side of the slit is more difficult to evaluate. For those cases where E_2 can be neglected, the crossover will occur at a distance to the right of the slit as shown in the right hand curve of Fig. 7. It will be observed that for ratio of d/r_0

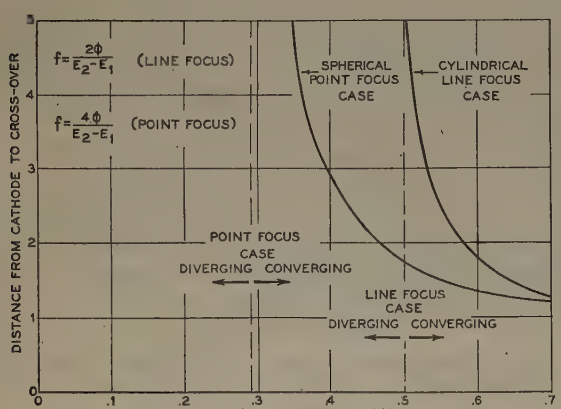

Fig. 7—Position of the crossover for line-focused and point-focused beams.

greater than 0.5 the beam will converge, while for values of d/r_0 of less than 0.5 the beam will diverge. The second curve on Fig. 7 will be considered later.

The analogous sort of spherical symmetrical flow, in which the electrons form a cone-shaped beam between spherical caps, is difficult to treat analytically. There is a different set of equipotentials for each angle of the cone occupied by the flow. The electrolyte tank approach must therefore be used and guns designed to meet specific requirements. The appropriate variations in potential with distance for which the electrodes are to be adjusted can be obtained from the work of Langmuir and Blodgett.[6,7] Their data are shown plotted in a form suitable for our use in Fig. 8. For convenience, curves are shown for both the cylindrical and the spherical cases, the abscissa is the ratio of the anode-cathode spacing to the cathode radius, and the ordinate is either their parameter α raised to the 4/3 power or their parameters[8] $(r\beta^2/r_0)^{2/3}$. When so plotted, the segments of the curves to the left of any specified abscissa value are linear plots to an arbitrary scale of the potential distribution in structures having a value of the ratio of spacing to cathode radius as specified by the abscissa value. For ex-

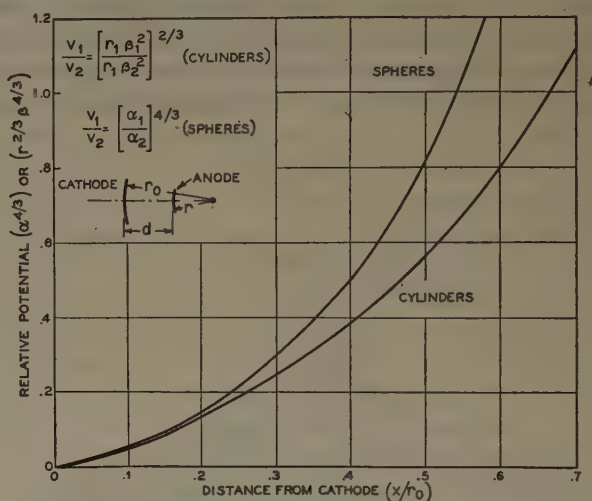

Fig. 8—Potential distribution between coaxial cylinders and concentric spheres with complete space charge. (Authors note. The second expression in the ordinate should read $(r^{2/3}\beta^{4/3}/r_0^{2/3})$.

ample, with a value of 0.5 for this ratio, the curve to the left of the abscissa 0.5 is the desired plot. To convert the potential scale into units of the anode potential, one need only divide ordinate values by the ordinate value corresponding to the limiting abscissa value, that is, by 0.83 (for the concentric sphere case), while distances from the cathode are given in terms of the cathode radius directly along the abscissa scale.

Design of a Point-Focused Gun

Now let us suppose that we are faced with the job of designing a point-focused gun. Before an intelligent choice can be made of the ratio of spacing to cathode radius, some consideration must be given to the lens action of the hole which must be cut in the anode to transmit the electron beam. As noted earlier, it is possible to compute this from the lens equation of Davisson, provided one knows the field conditions on the far side of the anode. With converging beams these are not known with certainty, so that a certain amount of judgment is involved. By referring again to Fig. 7, which

[5] C. J. Davisson and C. J. Calbick, "Electron lenses," *Phys. Rev.*, vol. 42, p. 580; November 15, 1932.

[6] I. Langmuir and K. B. Blodgett, "Current limited by space charge between coaxial cylinders," *Phys. Rev.*, vol. 22, pp. 347–356; October, 1923.

[7] I. Langmuir and K. B. Blodgett, "Current limited by space charge between concentric spheres," *Phys. Rev.*, vol. 24, pp. 49–59; July, 1924.

[8] For definitions of these parameters see references 6 and 7 above.

applies to the case in which this field can be neglected, it will be observed that convergence will occur for all values of cathode-anode spacing greater than 0.29. For values less than this, the beam will diverge. In the limit when the ratio of spacing to cathode radius approaches zero, the electrons appear to diverge from a point which is located behind the cathode surface by a distance of twice the cathode-anode spacing.

Having chosen a value of the ratio of anode-cathode spacing to the cathode radius on the basis of the desired beam convergence, we must next decide on the conical angle of the beam. This angle is intimately related to the desired gun perveance, defined as the ratio of the beam current in amperes to the 3/2 power of the voltage. Perveance is used, since it is a constant for any given structure under conditions of complete space charge, subject only to the restriction that only one potential difference is involved, or if more than one potential is involved the ratios between them are maintained constant. The value of this parameter as given by Langmuir and Blodgett when applied to a cone-shaped beam is

$$I/V^{3/2}=14.68\times10^{-6}\quad(1-\cos\theta)/\alpha^2$$

where θ is the cone angle measured from axis, and α is the same parameter plotted in Fig. 8, where it was seen to depend only upon a ratio of certain dimensions and not upon the absolute scale. From this it is seen that the perveance is independent of the physical size of the gun, being a function of its shape only. In passing, it should be noted that this independence of perveance on size is true in general for all structures in which the 3/2 power law is obeyed. This perveance equation is plotted in Fig. 9. The perveance equation for the cylindrical case is shown in Fig. 10. In using these charts it is convenient to remember that a perveance of 1×10^{-6} corresponds to a current of 1 microampere at 1 volt, 1 milliampere at 100 volts, and 1 ampere at 10,000 volts.

That portion of Fig. 9 to the left of an abscissa value of 0.29 is shaded, to indicate that a diverging beam would result if a circular hole is used in the anode to transmit the beam. For perveances greater than roughly 50×10^{-6}, ways must be found to circumvent this limitation.

Some trouble is to be expected for perveances even lower than this value, however, as a result of the reduced and nonuniform field at the cathode surface caused by field penetration through the hole. To assist in evaluating this effect, two additional geometric curves are shown on Fig. 9. These show the relationship between the cone angle and the cathode-anode spacing when the hole diameter is, respectively, equal to the spacing and equal to ½ the spacing.

An additional design step is required if one wishes to compensate for the anode hole. Consider, for a moment, space-charge flow between complete spherical surfaces. The perveance depends only upon the ratio of cathode-anode spacing to cathode radius. However, for this same structure in the absence of space charge, there will also exist a unique value for the off-cathode potential gradient. A hole cut into the anode will distort the field at the cathode and modify the off-cathode gradient, as well as altering the space-charge conditions. Compensating changes in the shape of cathode surface opposite the hole which tend to make the no-space-charge off-cathode gradient uniform, will at the same time tend to make the cathode emission uniform under space-charge

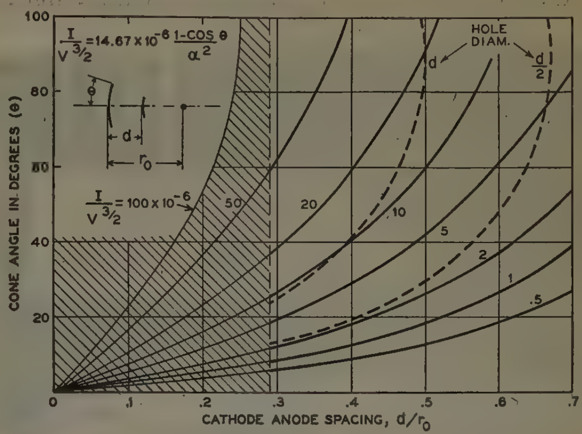

Fig. 9—Beam perveance for spherical caps.

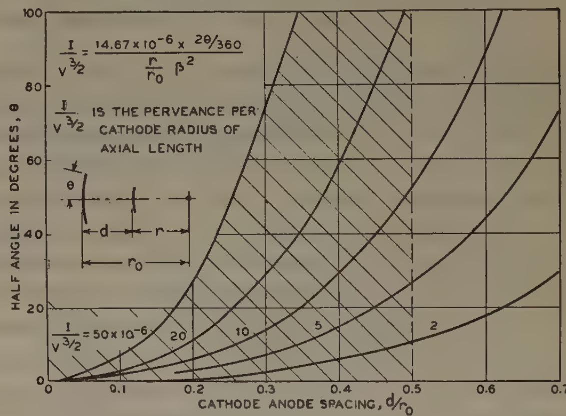

Fig. 10—Beam perveance for cylindrical segments.

conditions, and restore the perveance to its desired value. Only a moderate amount of compensation can be obtained in this way, since altering the shape of the cathode surface will alter the directions of the initial electron accelerations and this will introduce focusing difficulties if carried too far. The electrolytic tank can be used for this problem by setting up electrodes simulating the complete spherical case, introducing the hole in the anode sphere symmetrical with respect to the axis and investigating the off-cathode gradient. As non spherical surfaces are sure to result from this modification of the design procedure, we have normally omitted it. For cases where some compensation is essential, a number of quite different empirical design approximations have been used from time to time with nearly equal success. None of these methods is sufficiently fundamental to justify detailed description.

With these preliminary considerations out of the way, we can proceed to the electrolytic tank and lay out the

electrode design external to the beam. The design is obviously quite independent of the physical size, although the actual size of any physical gun is fixed by the desired current and by the permissible current density from the cathode.

Experimental Confirmation

As a check on the usefulness of this general method, a gun was designed and constructed to deliver 400 milli-

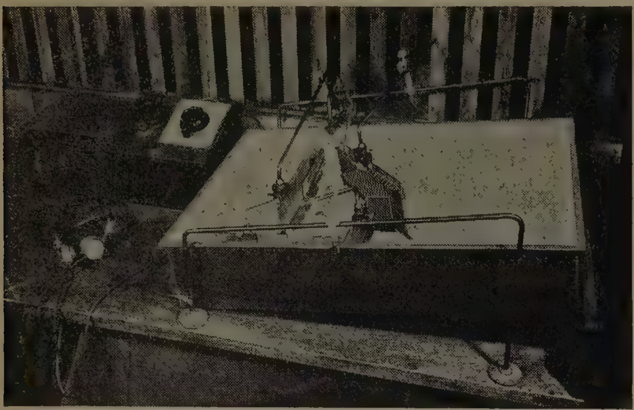

Fig. 11—Electrolytic tank set up for a point-focused gun.

amperes at a computed perveance of 6×10^{-6}. The cone angle was set at 42 degrees and the spacing at 0.47. No effort was made to compensate for the nonuniformity resulting from the anode hole. The electrolytic tank used for this purpose is shown in Fig. 11. This is simply a large developing tray, tipped at an angle. A piece of heavy plate glass with Cartesian co-ordinates etched on it forms the bottom of the wedge-shaped electrolyte. A series of line electrodes are spaced at equal intervals along the insulating sheet which simulates the edge of the beam. In this case this sheet makes an angle of 42 degrees with respect to the axis, as defined by the thin edge of the wedge. The actual electrode shapes which were finally chosen are shown in Fig. 12. This is a single-

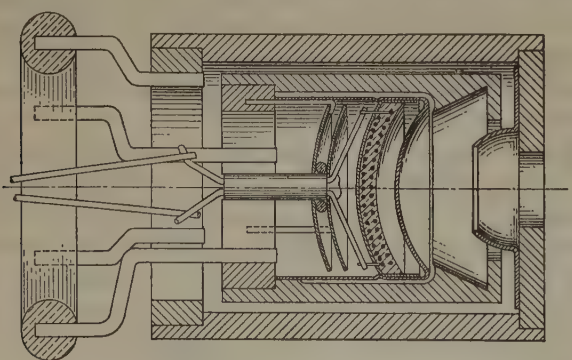

Fig. 12—Section view of a point-focused gun.

potential gun having one electrode at the cathode potential which in this case makes an angle of 67.5 degrees with the normal to the cathode surface at its edge, in accordance with the theoretical requirement. Attention is called to the fact that a double aperture is used in the anode. The second limits the penetration of any external fields which may be present into the region near the first aperture, and insures that the gun will focus more or less independent of the external conditions. While external fields will produce lens action at the second aperture, this lens is located fairly close to the final crossover position, and so has a fairly small effect. The second aperture also tends to suppress secondary electrons that are knocked out of the edge of the first aperture as a result of imperfectly focused primary electrons from the cathode.

How well this gun performed may be judged by referring to Fig. 13. Three curves are given, one showing the current to a collector placed at some distance from the gun, the second showing the current to a thin disc

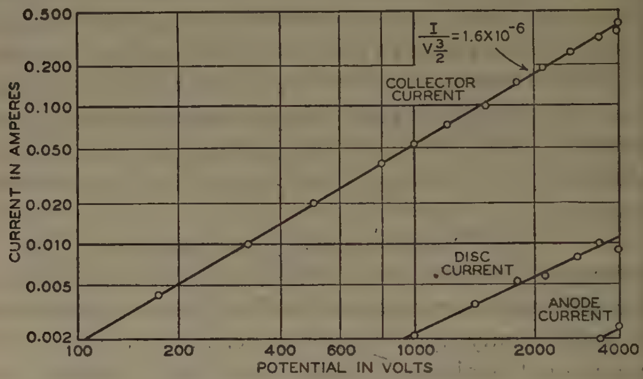

Fig. 13—Experimental point-focused gun data.

containing a 0.100-inch hole placed at the computed crossover point, and the third showing the current to anode of the gun. It will be observed that only a negligible amount of current was deflected to the gun anode, and that something over 96 per cent of the total current passed through the 0.100-inch hole. One disturbing feature was the low perveance, the measured value being 1.6×10^{-6} as compared with the computed value of 6×10^{-6}. This can be explained by the failure to compensate for the hole in the anode.

A series of such guns is shown in Fig. 14. In some of these guns the agreement between calculated and

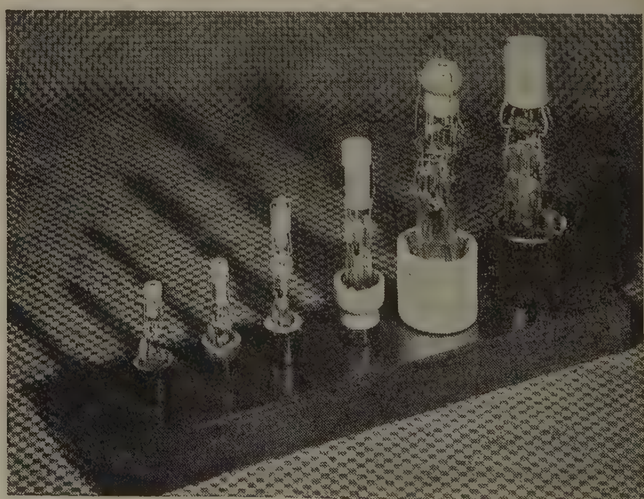

Fig. 14—A series of point-focused guns.

measured perveance is considerably better than for the example quoted. In fact, when proper allowance is made for the effects of the anode hole, the calculated and measured perveances are usually within normal engineering tolerances.

The Current Distribution in a Point-Focused Beam

The current distribution within the beam produced by such a gun is of some interest. While the theoretical basis for the design naively assumes a uniform current distribution throughout the beam, a number of factors are neglected. The nonuniform field at the cathode, imperfection in the matchings of boundary conditions, the removal of edge electrons by the anode, thermal velocities, space-charge effects in the beam after it leaves the anode, to name a few, all tend to destroy this uniformity.[9,10]

To investigate the actual distribution, a probe tube was constructed as shown in Fig. 15, containing the gun to be tested, a probe electrode containing a 0.010-inch slit which can be moved across the beam at any desired

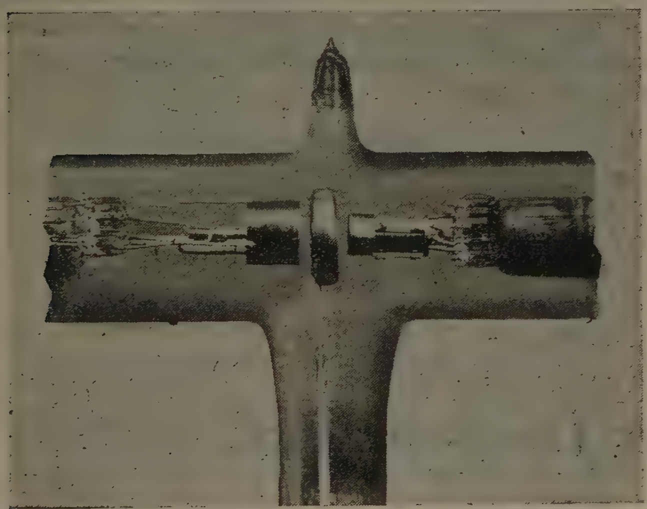

Fig. 15—Probe tube for studying the current distribution in the beam.

distance from the gun, and a suitably shielded collector to measure the current passed by the slit. Ideally, one should measure the current passed by a small hole moved across a diameter of the beam rather than using a slit. The lineup problem makes this an impracticable procedure. However, from the shape of the current distribution observed with a slit, it is possible to obtain a fair idea of the radial distribution. In particular, if the radial distribution is uniform, the integrated distribution curve will be semielliptical, that is, it will have sharp edges. On the other hand, if the radial distribution is Gaussian, an error-function curve will result. These two cases are illustrated in Fig. 16.

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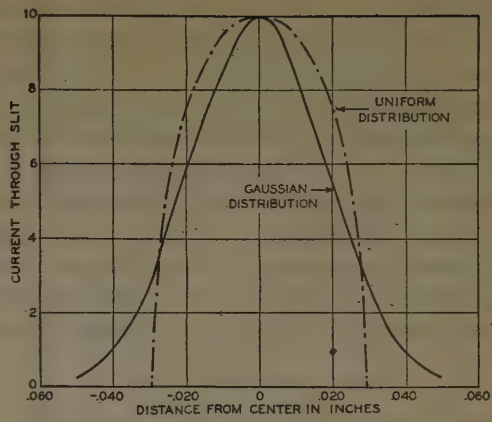

Fig. 16—Calculated probe data for idealized distributions of current density.

Experimental data obtained with the probe tube are shown in Fig. 17 for three different positions of the probe with respect to the gun, and for an accelerating field external to the gun. Very near the gun the distribu-

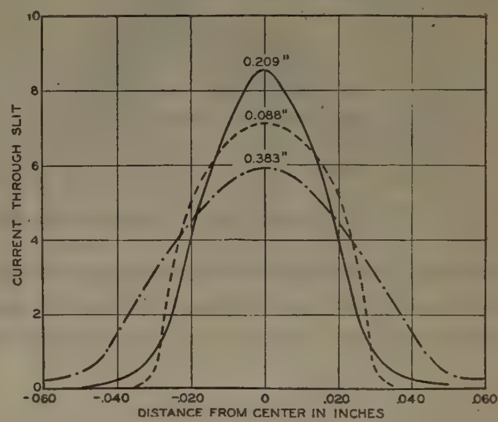

Fig. 17—Probe data at different distances from gun.

tion appears to be quite uniform, except for a slight tail which may be partly due to secondary emission. At greater distances, the distribution becomes more nearly Gaussian with a preliminary increase in current density at the center, and a subsequent decrease as the crossover distance is exceeded. Under the best conditions, the maximum current density appears to be well over one

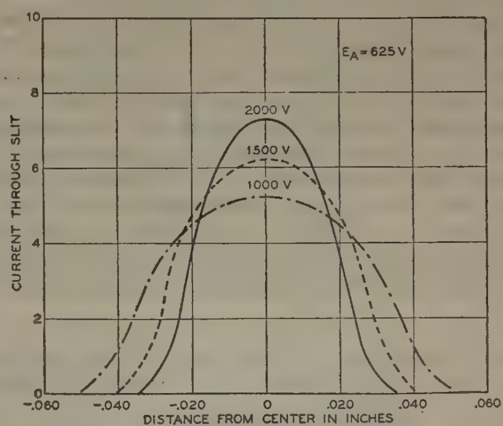

Fig. 18—Effects of accelerating field on beam diameter.

half of the limiting value imposed by thermal velocities. It should be pointed out that the actual shape of the beam cannot be directly inferred from these curves, since the motion of the probe electrode toward or away from the gun changes the field conditions, and so alters the size of the beam. Some idea of the effect of these fields can be obtained from Fig. 18, showing data taken with a fixed probe distance, but different accelerating fields. It will be observed that the accelerating field changes the size of the beam, but it does not have much effect on the essential shape of the current distribution.

Higher Perveance Guns

As mentioned earlier, there appears to be a practical limit to the beam perveance which can be obtained with

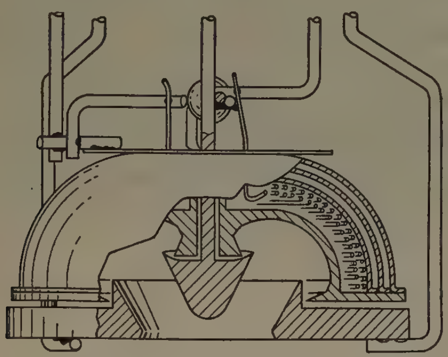

Fig. 19—A toroidal gun producing a point-focused beam.

a point-focused beam of the simple type which has just been discussed. The gun shown in Fig. 19 was constructed in an effort to obtain a still higher perveance. The cathode surface was made in the form of an axially symmetric section of the surface of a toroid. Since the space-charge relationships between concentric toroids had never before been worked out, an approximation solution was used. The necessary electrode configurations were obtained in the electrolytic tank to produce a hollow conical-shaped beam designed to focus to a point on the axis. The experimental gun had a perveance of 30×10^{-6} as compared with a calculated value of 40×10^{-6}, and appeared to have a very sharply defined crossover.

By using a different portion of the toroidal surfaces, a second gun was designed producing a tubular beam of electrons with a measured beam perveance of 66×10^{-6}. If still higher perveances are required, accelerating grids can be used without invalidating the fundamental correctness of the design method.

Acknowledgments

Credit has already been given for the valuable contributions to the theory made by Dr. J. R. Pierce. The writer wishes to acknowledge the collaboration and assistance of two of his former associates, Mr. C. V. Parker and Lt. A. Eugene Anderson, and to express his appreciation to Mr. J. P. Laico for the mechanical design of the electron guns.

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Recent Transformer Developments*

REUBEN LEE†, ASSOCIATE, I.R.E.

Summary—**Descriptions of new transformer steel and insulation are given together with new circuits and applications involving transformers. Instances are cited of size reductions and extensions of frequency ranges in which transformers may be used.**

Four outstanding and almost parallel developments have made possible a variety of improvements in radio transformers. These developments are: (I) new available core steels, (II) new insulation, (III) new circuits, and (IV) new applications. Stated thus, these developments may not sound very remarkable. The aim of this paper is to show how in some cases these developments make possible drastic size reductions, even to the point of eliminating transformers completely, and how in other cases transformers are used where formerly none were used. A range of instances all the way from complete disappearance of a transformer species to the evolution of a new one should be worth the attention of radio engineers.

* Decimal classification: 621.314.3×R382.1. Original manuscript received by the Institute, September 1, 1944; revised manuscript received, November 22, 1944.

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I. New Available Steel

THE FIRST of these developments, namely, transformer steel, is a revolutionary advance in the art of making electrical sheet steel. Operating flux densities have been increased 30 per cent, losses have been reduced, and permeabilities increased several fold compared to ordinary silicon steel. Outstanding among the new steels is "Hipersil", a steel in which the direction of grain orientation is closely controlled during the manufacturing process. The new material requires that the flux flow in this preferred or grain-oriented direction (see Fig. 1) in order that the full benefit may be realized. For this reason, the cores are no longer stamped out of thin sheets, but are wound from strip and formed on a mandrel. The wound core is then annealed to take out the winding strains, impregnated with a bond, and cut in two to permit assembly with the windings or coils.

ollowing the cutting operation, the burrs are removed y successive grinding and etching. After the core is as- mbled with the coil, it is held together by means of a eel band. Because of the similarity of the shape of the vo halves of the core to a letter "C", the cores are

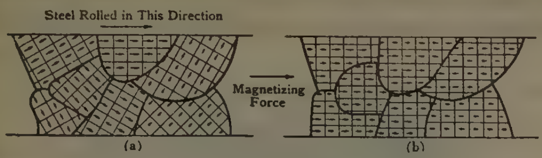

Fig. 1—Grain orientation.

Fig. 2—Hipersil core.

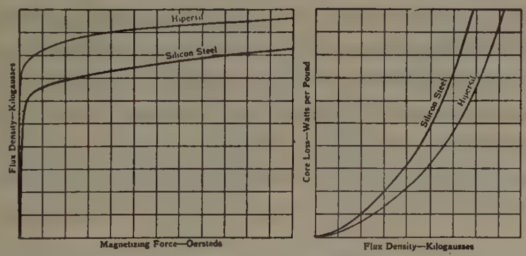

Fig. 3—Saturation curve comparisons, Hipersil versus Si steel.

nown as Type C cores. Typical cores made in this ianner are shown in Fig. 2, and the improved perform- nce in Figs. 3, 4, 5 and 6. Transformer assemblies are hown in Figs. 7 and 8.

The material is rolled in three major thicknesses:

No. 29 gauge (about 13 to 14 mils thick) for frequencies up to 400 cycles

5 mils thick for frequencies higher than 400 cycles

2 mils thick for frequencies in the low and medium radio-frequency bands.

The superior properties of these steels can be utilized 1 one of three ways: reduction in size, improved per- ormance, or both. Size reductions of 50 per cent are ommon at power frequencies using the 13-mil thick naterial. The 5-mil thickness is most commonly used in

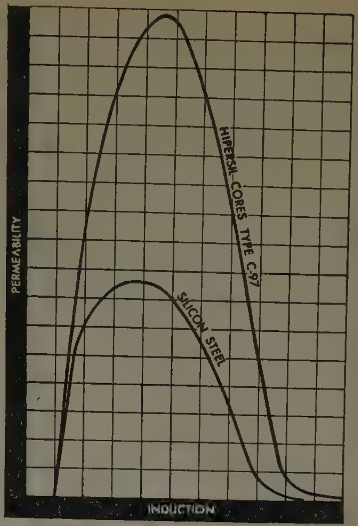

Fig. 4—Permeability of Hipersil and Si steel.

aircraft and portable equipment, where higher frequencies of 400 and 800 cycles are used. The need for high voltages in such equipment has fortunately been met by the advent of this low-loss, high-saturation-point steel. Fig. 9 shows comparative sizes of transformers of the same rating; the two larger units are suitable for 60-cycle operation, and the smallest for 400 cycles. Still more striking size reductions are made possible by the 2-mil thick material within the frequency range for which it is intended. In fact, it can be said that both of the thinner gauge materials make possible in their own fields the building of transformers not formerly practicable.

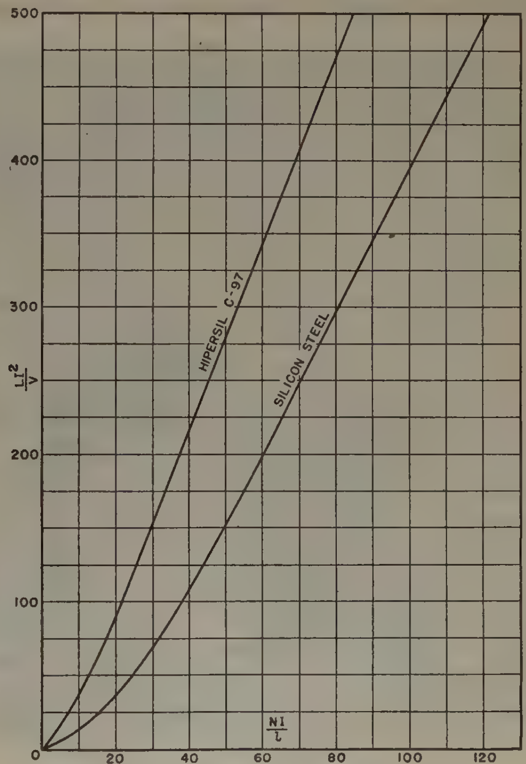

Fig. 5—Choke sizes in Hipersil and Si steel.

A glance at the fundamental transformer equation $e = Nd\phi/dt$ will reveal how the increase in magnetization has effected a reduction in size. If it is possible to increase the total flux, it is also possible to increase the voltage for a given number of turns, or for a fixed voltage

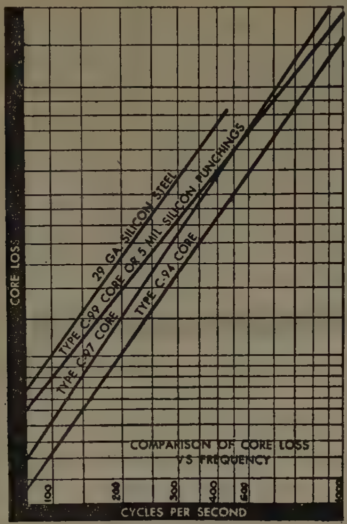

Fig. 6—Comparison of core loss versus frequency.

to reduce the number of turns. This is true at any frequency. But the leakage flux is also proportional to turns, so that if the total turns are reduced, the leakage flux decreases, and therefore better high-frequency performance is made possible.

II. New Insulation

The second development consists in the invention of a radically new varnish. Varnishes used for impregnation of electrical coils have until lately been diluted to some degree, at least, by the use of solvents to lower the viscosity in order to permit full penetration of the windings. When the coils are baked, the varnish dries, but is left with tiny holes through which moisture can penetrate, and in which corona may form. Eventually, this corona destroys the insulation. It is, therefore, necessary to allow large clearances for high voltages or to immerse

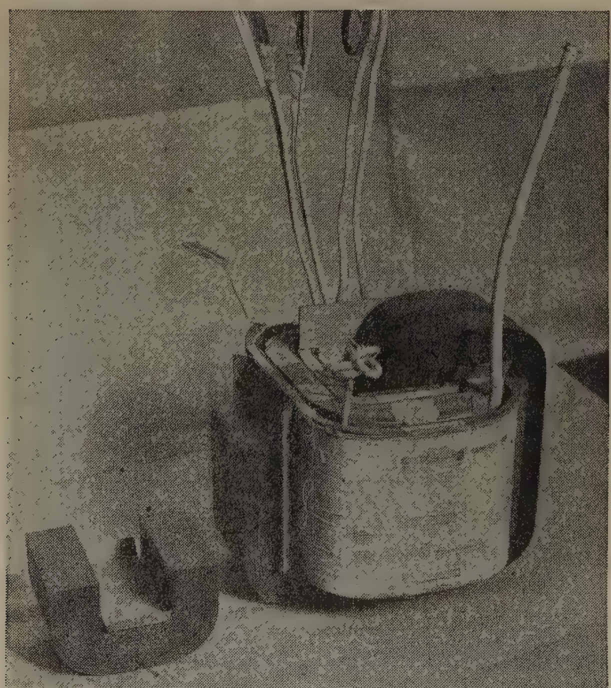

Fig. 7—Partly assembled transformer.

Fig. 8—Radio-transformer coil and core assembly.

the coils in oil. Either of these alternatives increases the size of a high-voltage transformer compared to that of a low-voltage transformer.

A new varnish (marked "Fosterite" after the inventor, Newton C. Foster of the Westinghouse research staff) changes from a liquid to a solid state with only slight change in volume. It is a polymerizing resin of low viscosity, requires no solvent and with care can be made to produce 100 per cent filling of coil interstices. Because of this excellent filling, it is possible to reduce voltage clearances to smaller values than formerly were possible, and therefore to obtain a pronounced reduction in size. Likewise, because of the fact that all air pockets are filled, moisture cannot penetrate the windings, and

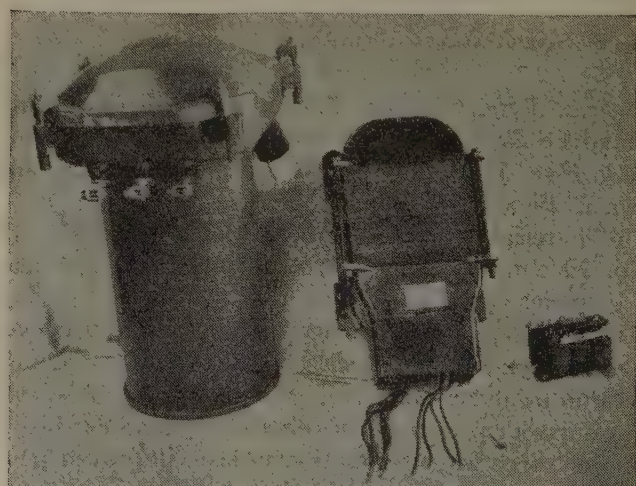

Fig. 9—Comparison picture of oil and dry distribution transformers with dry aircraft transformer.

much apparatus can be sealed effectively by impregnating with Fosterite. This is a great help in the reduction of size of small units. Especially notable are the protection and long life afforded to transformers containing small wire sizes and used in tropical atmospheres. Units with small wire last about one week in the tropics unless they are sealed to prevent moisture from entering the coils. No varnish, wax, gum or other material hitherto has given this protection.

Fosterite has low losses at radio frequencies. Its power factor is approximately 1 per cent at 1 megacycle, compared with 4 per cent for ordinary varnish. Its use, therefore, can be extended to radio-frequency components such as capacitors, chokes, and resistors. But more pertinent to this discussion is the fact that it affords for the first time a low-loss insulating compound for transformers operating at radio frequencies. Thus by the double advantage of decreased voltage clearances and low loss, Fosterite makes size reductions possible which have a wide bearing on radio-frequency performance.

III. New Circuits

Typical of the third kind of development is the elimination of transformers in Class B driver stages, particularly the drivers of high-power Class B modulators for broadcast stations. The requirements for driver transformers are unusually difficult. The transformer load is nonlinear, in that grid-current peaks constitute wide departures from sinusoidal shape. The driver tube must deliver these instantaneous peaks although the average load is very low; otherwise distortion will appear in the modulator audio output and therefore in the radio-frequency envelope. The grid-current peaks are the equivalent of higher order harmonic currents, and to insure their appearance in the modulator grid current requires an extension of the driver-transformer frequency range at both ends: on the high-frequency end because of the decreased leakage inductance necessary to allow the higher currents to flow, and on the low-frequency end to prevent transformer-magnetizing current, itself nonlinear, from loading the driver tube to the point where it will not deliver the peak grid power.

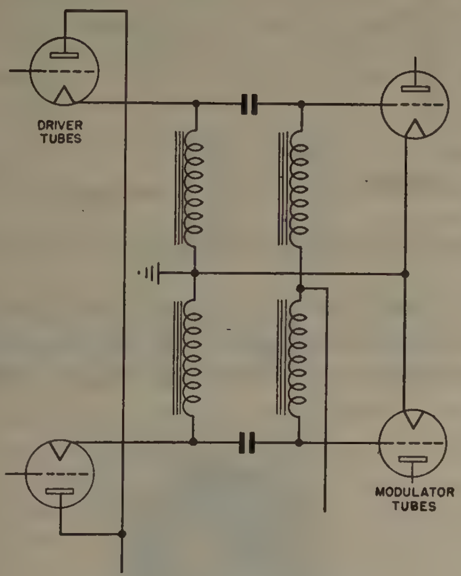

Fig. 10—Cathode-follower circuit.

Fig. 11—Rear of exciter cubicle, 50 kilowatt transmitter.

These difficult conditions require transformers of exceptionally large size. For example, a $7\frac{1}{2}$ kilovolt-ampere driver transformer weighs two tons; a 60-cycle distribution transformer of the same rating and voltage class weighs 250 pounds (Fig. 9, left-hand unit). For low (1 to 2 per cent) over-all harmonic distortion, the driver-transformer design becomes impracticable. Hence the occasion arises for dispensing with the driver transformers entirely. This is accomplished by the cathode follower circuit, Fig. 10, which for a push-pull amplifier takes the form of a symmetrical pi filter. The two audio input chokes connect the driver-tube cathodes to ground and carry their plate current. Coupling condensers connect these chokes to the modulator-tube grid chokes, which carry modulator grid current. Sizes of chokes and coupling condensers are chosen to give approximately constant impedance from the lowest audio frequency up to the higher harmonics of the highest audio frequency, and insure that pronounced resonance effects throughout the frequency range are avoided. Leakage inductance is now eliminated, and the chokes are of reasonable dimensions. In Fig. 11, the filter components are

mounted in the exciter cubicle; a transformer for this purpose would be too large to locate internally.

The cathode-follower circuit is advantageous in another way. The presence of leakage inductance in a driver transformer results in high audio-frequency phase shift between driver and grid voltage. This is nonexistent in the coupling-condenser scheme. Since inverse feedback is often applied to audio amplifiers to reduce distortion to a low figure, the absence of phase shift is a great advantage. It is true that the low frequency at which phase shift appears must be kept below the audio band, but this can be done without excessively large components.

IV. New Applications

Many of the recent advances in high-frequency technique are characterized by the use of nonsinusoidal wave shapes. Some of these shapes have very steep fronts. They are equivalent to high frequencies of the order of 300 to 3000 kilocycles. To be used at such frequencies, cores must have very low losses, and windings must present as little series impedance or insertion loss as possible. Additionally, the core material must have as high a permeability as can be obtained. An ideal transformer would have infinite inductance on open circuit and zero inductance when short-circuited. It would also

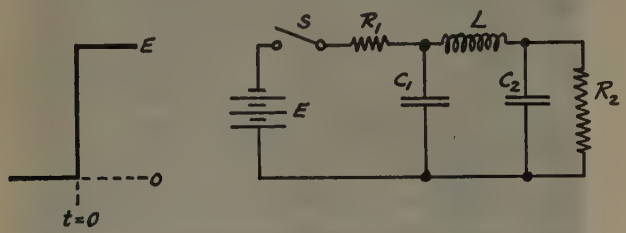

Fig. 12—Equivalent transformer circuit for front of pulse.

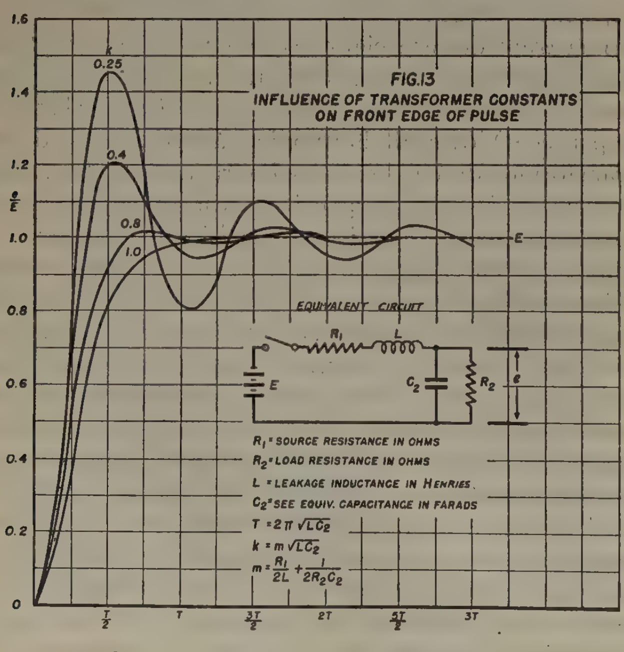

Fig. 13—Performance for front of pulse.

have low distributed capacitance and zero loss. High open-circuit inductance and low losses can be obtained for these applications by the use of thin-gauge Hipersil which also contributes to the reduction of size, and therefore of leakage inductance and capacitance. In these cases, small size is not merely desirable; it is necessary for obtaining the proper performance. For the steep wave front a good transformer can be considered as an L or pi filter section (Fig. 12) whose wave-front response is shown in Fig. 13.

After the voltage has reached a steady value, often it must be maintained at or near this value for a certain period of time. It is a striking fact that this constancy of voltage is partly achieved through the character of the loads found in these high-frequency applications, which are commonly nonlinear as shown in Fig. 14, so that

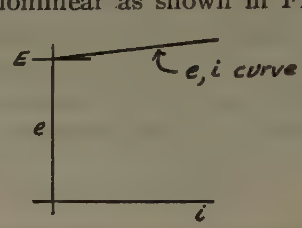

Fig. 14—Nonlinear load characteristic.

large changes of current can be had without much change in voltage. In many such applications, the current change is the more important of the two. By suitably proportioning the leakage inductance and distributed capacitance for a given load, it is possible to obtain the current and voltage wave shapes shown

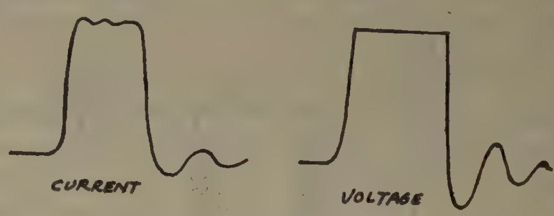

Fig. 15—Oscillograms of voltage and current wave shapes.

in Fig. 15 and thereby give the desired performance. This requires extreme care on the part of the designer but even this care would avail the designer nothing were

Fig. 16—Pulse transformer.

not for the availability of materials which make possible the small size essential to obtain the required performance.

An example of the kind just mentioned has a Hipersil core, Fosterite-filled coils and the following characteristics:

Voltage ratio 4000/8000

Voltage rises to 90 per cent of final value in $\frac{1}{4}$ microsecond

Voltage stays constant within plus or minus 5 per cent for 2 microseconds

Maximum flux density in core 8000 gausses

Efficiency 88 per cent

Weight 1 pound 1 ounce

Dimensions $3\frac{1}{2} \times 3 \times 2$ inches (Fig. 16)

Transformers are now used in many such applications where formerly they could not be used, and where great pains had to be taken to eliminate them. Although the developments recounted here preceded the war, their application has been speeded up by it. It is to be hoped the day will soon arrive when more constructive use can be made of such transformers.

A Resonant-Cavity Method for Measuring Dielectric Properties at Ultra-High Frequencies*

C. N. WORKS†, T. W. DAKIN†, AND F. W. BOGGS†

Summary—**A re-entrant cylindrical cavity has been adapted to measure the dielectric constant and power factor of small disk samples of insulating materials. The methods of measurement, mechanical details, and electrical coupling and detecting circuits are all described. A single cavity can be utilized only over a frequency range of about 1.5:1 ratio from lowest to highest frequency. Therefore, several different sized cavities would be required to cover a range of frequency from 50 to 1000 megacycles. An accuracy of ±0.00005 in tan δ and ±1 per cent in dielectric constant may be obtained in routine measurements. Because the cavity has a very high Q (>2000), it is much more sensitive to low power-factor dielectric samples than any conventional coil-and-capacitor resonant circuit.**

The chief advantages of this method are that the operation of the apparatus is simple, very rapid, and similar to the susceptance-variation technique now used at lower radio frequencies. Also, the involved computations usually found in other methods operative in this frequency range are eliminated.

I. Introduction

THE frequency range of 50 to 1000 megacycles has always proved a difficult range in which to measure the dielectric constant and loss of solid materials, because of residual lead and electrode inductance, resistance, and capacitance, and the difficulty of obtaining a solid sample to conform to the shape of the measuring device. Transmission-line methods of measuring a lumped impedance which have been recently treated by Hempel,[1] Kaufman,[2] Laville,[3] Nergaard,[4] Miller and Salzburg,[5] and Chipman,[6] can of course be used to measure a dielectric sample considered as an impedance, but the problem remains here of attaching leads and electrodes to the dielectric so that they will not enter into the measurements, or of correcting for them if they do. Coaxial-transmission-line methods,[7,8] where a section of (usually resonant) coaxial line is filled with the dielectric, are rigorous and satisfactory, but they require well-machined annular samples of considerable length, especially at the lower frequencies. Another method especially adaptable to high loss materials is that described by Wyman,[9] where the phase angle and capacitance of a dielectric sample in this frequency range is compared to that of a standard sample with a cathode ray tube. Liquids can be conveniently measured by filling a coaxial line, and liquids surrounding a parallel transmission line have been measured by Drude.[10,11] Liquids can also be measured readily in small coil and capacitor resonators which are totally immersed.[12]

At somewhat lower frequencies, below 100 megacycles

* Decimal classification: R281. Original manuscript received by the Institute, October 25, 1944. Presented, Summer Meeting, American Institute of Electrical Engineers, St. Louis, Missouri, June 29, 1944; Rochester Fall Meeting, Rochester, New York, November 13, 1944. To be published in the *Transactions of the A.I.E.E.*, 1944. Published by permission of the American Institute of Electrical Engineers.

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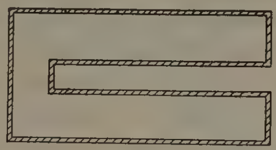
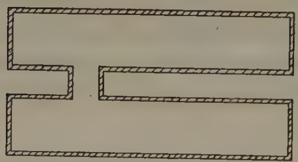
and down to several hundred kilocycles, the susceptance-variation technique of Hartshorn and Ward[13] has the advantage of practically eliminating the effect of series lead and electrode inductance and resistance. This method using a coil-and-capacitor arrangement has been applied up to 100 megacycles. At this frequency the dimensions of the usual type of coil and capacitor needed to obtain resonance start to become unusually small. The usual circuits must, therefore, be modified. The coils used also have relatively low Q values so that insertion of low-loss dielectrics into the capacitor lowers the Q values of the circuit only slightly. The sensitivity of the apparatus, therefore, is relatively poor, when measuring low-loss materials. The resonant-cavity method described in this paper obviates most of these difficulties and has many advantages over the older methods.

II. Theory of Measurements

The transition of the coil and parallel-plate capacitor resonant circuit at higher frequencies to a capacitor with a series of loops in parallel around it and from thence to a doubly (or singly) re-entrant closed cylinder is logical. This re-entrant cylinder is now a closed cavity capable of being resonated. It may also be thought of as a short-circuited quarter-wavelength transmission line with a capacitor at the open end. The capacitor actually makes the physical length of the line less than $\frac{1}{4}$ wavelength. Cross sections of a singly re-entrant cavity and a doubly re-entrant cavity are shown in Fig. 1.



Single re-entrant cavity.



Double re-entrant cavity.

Fig. 1

The dimensions of such cylinders, resonant in the frequency range 50 to 1000 megacycles are quite reasonable, their lengths varying from about 2 feet to 2 inches. This length is governed partly by the average capacitance at the end, and partly by the ratio of the radii of the inner and outer conductors.

Capacitance

The dielectric under consideration is assumed to extend flush to the edges of the electrode posts and fill completely the space between the electrodes. This is not necessary, for the dielectric sample may be smaller than the area of the posts and may even have an air gap in series with it. In such cases, standard equations for a combination of series and parallel dielectrics (air and sample) may be used to obtain the values for the sample after the overall dielectric properties of the space between the electrodes have been determined.

Let only that part of the apparatus which holds the dielectric be considered. The capacitance between the ends of the re-entrant cylindrical posts when the dielectric is in place is $C_x + C_{e1}$. These and all following symbols are defined below.

Definition of Symbols

A = area of electrodes in the cavity in square inches.

a = outside radius of inner conductor of cavity in centimeters.

b = inside radius of outer conductor of cavity in centimeters.

c = velocity of light in centimeters per second.

C = capacitance between the ends of the re-entrant posts (electrodes) in the cavity at resonance.

C_x = capacitance of sample being measured.

C_T = total equivalent capacitance of cavity considered as a resonant coil and condenser.

C_{a1} = air capacitance, excluding fringing, between parallel electrode faces at the separation existing when the sample is in place in the cavity. Unless there is an air gap between the sample and the electrodes, this is the calculated air capacitance of the sample.

C_a = air capacitance of the sample. This equals C_{a1} if the sample has the same diameter as the electrodes, and is in contact with them.

C_{e1} = fringing air capacitance with the electrode separation existing when the sample is in place in the cavity.

C_{a2} = air capacitance, excluding fringing, between the parallel electrode faces at separation 2 when the sample has been removed and the cavity retuned to resonance by decreasing the electrode separation.

C_{e2} = fringing capacitance at separation 2, as above.

$C_1 = C_{a1} + C_{e1}$ = approximately C_{a1}

$C_2 = C_{a2} + C_{e2}$ = approximately C_{a2}

C_1', C_1'' = capacitances between the electrodes of the empty cavity, or ($\Delta C_1 = C_1' - C_1''$) of an identical wavemeter, at f_1' and f_1'', respectively.

C_2', C_2'' = capacitances between the electrodes of empty cavity, or ($\Delta C_2 = C_2' - C_2''$) of an identical wavemeter at f_2' and f_2'', respectively.

D_1 = separation of electrodes with the sample in the cavity.

D_2 = separation of electrodes when the sample has

[13] L. Hartshorn and W. H. Ward, "The measurement of the permittivity and power factor of dielectrics at frequencies from 10^4 to 10^8 cycles per second," *Jour. I.E.E.* (London), vol. 79, pp. 597–609; November, 1639.

been removed and the cavity retuned to resonance.

D_1', D_1'' = separation of electrodes in the cavity or the wavemeter identical to the cavity when tuned to frequencies f_1', f_1''.

D_2', D_2'' = separation of electrodes of the cavity at the half-power points when the cavity is empty.

δ = loss angle.

f = frequency of oscillation, cycles per second.

$(Q_1 = Q_T) = Q$ of cavity with dielectric inserted.

$(Q_2 = Q_0) = Q$ of cavity when dielectric has been removed.

S = length of internal conductor of coaxial part of cavity in centimeters.

ΔS = change in S on retuning cavity to resonance after removing sample. This is the same as the change in separation of the electrodes.

σ = conductivity of metal covering inside of cavity in mhos per centimeter (5.8×10^5 for copper).

ω = angular frequency of oscillations.

Z_0 = characteristic impedance of coaxial part of cavity.

V_0 = voltage of resonance with sample removed from cavity.

V_T = voltage of resonance with sample inserted.

r_0 = radius of electrode in centimeters.

r_s = radius of sample in centimeters.

f_1' f_1'' = frequency at the half-power points with the sample in the cavity.

f_2', f_2'' = frequency at the half-power points with the cavity empty.

$1/Q_x = \tan \delta_x$ = dissipation factor of the dielectric sample $\cong \cos \theta$, the power factor

Tan δ_D = dissipation factor of dielectric which fills the entire cavity.

Tan δ_0 = dissipation factor of the empty cavity.

ϵ' = dielectric constant.

f_1 = resonant frequency of cavity with sample inserted.

E = electric field strength.

Note: Capacitance is in farads in all equations.

When the dielectric is removed, and the gap between the electrodes (ends of the re-entrant posts) has been closed sufficiently so that the cavity is resonant again at the same frequency, we have capacitance between the electrodes equivalent to what we had before. This capacitance is given by the expression $C_{a2}+C_{e2}-(dC/dS)\Delta S$, where $(dC/dS)\Delta S$ is the correction term for the small change in length of the coaxial line which necessarily takes place when one of the posts is extended inward to diminish the gap.

Now, since the circuit is resonant in each case, the following relation is true:

$$C_x + C_{e1} = C_{a2} + C_{e2} - (dC/dS)\Delta S. \quad (1)$$

The capacitance of the electrode arrangement of two parallel cylinder faces is determined by calibration using an audio-frequency bridge. This calibration is carried out so that the difference between the total interelectrode capacitance (including the fringing capacitance) at any two spacings of the gap is determined accurately. Thus from this calibration we know $(C_{a2}+C_{e2})-(C_{a1}+C_{e1})$. Then we have, using (1),

$$C_x = (C_{a2} + C_{e2}) - (C_{a1} + C_{e1}) + C_{a1} - (dC/dS)\Delta S. \quad (2)$$

With the exception of the last term, this is the same expression as is used in the susceptance-variation method to obtain the capacitance of an unknown. It is subject to an approximation, which is valid only if the change in S, ΔS, to retune the cavity to resonance after the sample is removed is small compared to S. We also have made the assumption that C_{e1}, the fringing capacitance with the sample at spacing 1, is the same as without the sample for the same spacing. The correction term for the change in length $(dC/dS)\Delta S$ is usually less than 5 per cent of C_x, so that a small error in $(dC/dS)\Delta S$ has a second-order effect on the value of C_x.

This correction term is derived as follows: The resonant frequency of a short-circuited transmission line with a capacitor at one end is given by

$$Z_0 \tan (2\pi fS/c) = (1/2\pi fC). \quad (3)$$

The frequency characteristic of a re-entrant resonant cavity for the general case where the radius is appreciable compared to a quarter wavelength has been treated in some detail by Hansen.[14] However, if the radius of the resonant cavity is not very large compared to a quarter wavelength, its resonant frequency may be obtained to a good approximation by considering it a short-circuited transmission line with a capacitor at one end. The dimensions of the cavities were so chosen that (3) is very nearly satisfied. In particular, care must be exercised in choosing the radius of the cavity so that it will not be a large fraction of the wavelength. If this is not done the correction term will be less accurate than desired.

By differentiating (3) with respect to the gap distance

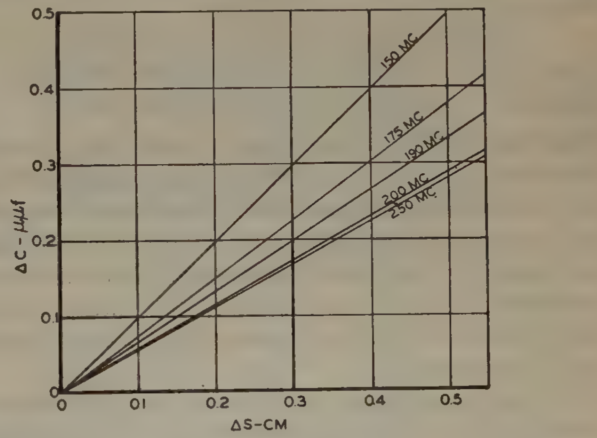


Fig. 2—These curves show the change in capacitance versus change in separation of electrodes at constant frequency. (200-megacycle cavity used in this research.)

[14] W. W. Hansen, "On the resonant frequency of closed concentric lines," *Jour. Appl. Phys.*, vol. 10, pp. 38–45; 1939.

S, the following expression for the correction term is obtained:

$$\frac{dC}{dS}\Delta S = -\frac{(2\pi f)^2 C_2^2}{c} 138 \log_{10}\frac{b}{a}\left(\sec^2\frac{2\pi f S}{c}\right)\Delta S. \quad (4)$$

It has been found practicable to plot graphs of this function versus ΔS for various values of f and C_2, from which graphs interpolation can be made to obtain the correction term at any particular measurement. Such a series of curves is shown in Fig. 2.

The assumptions which have been made in this method of measurement are justified experimentally in the results which have been obtained for the dielectric constant. Measurements made on samples of various thicknesses of the same material agree well, which would not be the case if these assumptions were not valid. Measurements made on materials like polystyrene and quartz, which have very little change of dielectric constant over a wide range of frequency, agree well with lower- and higher-frequency measurements by independent methods and those of other experimenters.

Dissipation Factor

It remains now to determine the dissipation factor $\tan\delta_x$ of the dielectric sample. In a resonant circuit, the following relation holds:

$$\tan\delta_{\text{total}} = \tan\delta_0 + \tan\delta_D \quad (5)$$

where $\tan\delta_0$ is the dissipation factor of the empty cavity. Included in $\tan\delta_0$ are all the effects due to coupling elements, measuring elements, and the ohmic resistance of the inside surface of the cavity. Tan δ_D would be the dissipation factor of the sample being measured if the sample filled the whole cavity, but since the sample does not fill the whole cavity, $\tan\delta_D$ is less than the dissipation factor of the sample by a factor (C_x/C_T). Then, $\tan\delta_D = \tan\delta_x C_x/C_T$. From (5) and the relation between $\tan\delta_D$ and $\tan\delta_x$ the following expression is obtained:

$$\tan\delta_x = (C_T/C_x)\tan\delta_{\text{total}} - (C_T/C_x)\tan\delta_0. \quad (6)$$

Equation (6) may also be written in its equivalent Q form

$$1/Q_x = (C_T/C_x)(1/Q_T) - (C_T/C_x)(1/Q_0). \quad (6a)$$

Now $\quad 1/Q_0 = \Delta C_2/2C_T, \quad$ and $\quad 1/Q_T = \Delta C_1/2C_T \quad$ (6b)

whence $\quad \tan\delta_x = \Delta C_1/2C_x - (\Delta C_2/2C_x). \quad$ (6c)

Therefore, it is not necessary to know the total equivalent capacitance of our circuit (cavity) if the Q values are measured by changing the capacitance in our cavity by a known amount. ΔC_1 and ΔC_2 are, respectively, the variation in capacitance necessary to detune from one half-power level of resonance to the other, when the cavity is empty (ΔC_2) and when the cavity has dielectric in it (ΔC_1).

In a conventional coil-and-capacitor circuit it is not difficult to detune from resonance to half power by changing the capacitance, for only an additional parallel vernier capacitor is necessary. In a re-entrant cavity it is more difficult, since the only variable capacitance is that between the re-entrant ends. This may be varied readily when there is no dielectric in place, but complications enter when there is a dielectric sample between the re-entrant ends. Therefore, an indirect measurement of the ΔC value must be made. This can be readily accomplished if a value of dC/df is known. Then the frequency f may be varied to detune the cavity to half power from maximum resonant voltage. From a Δf value, a corresponding ΔC value may be obtained from a calibration chart.

The dissipation factor of the empty cavity is generally but 1/10 of the smallest value obtained with the usual circuit elements. This makes the device much more sensitive for measuring very-low-loss dielectrics than the susceptance-variation circuit used by Hartshorn and Ward.[18] The theoretical Q of such a cavity will be of the order of magnitude of that of a resonant quarter-wavelength line of the same cross section. The expression for the Q of a coaxial line of this sort is

$$Q = 4\pi\sqrt{\sigma/10}\, b[(\log_e b/a)/(b/a+1)]\sqrt{f}\times 10^{-4}. \quad (7)$$

The optimum Q is obtained with a ratio of b/a equal to about 3.6. Because of certain design features in the actual cavity, such as a bellows forming part of the inner conductor, and because of energy absorbed by measuring probes and the effect of the coupling-in loop, the theoretical Q which can be as high as 10,000 is never reached. The authors usually obtained $\frac{1}{4}$ to $\frac{1}{2}$ of the theoretical Q for the empty cavity.

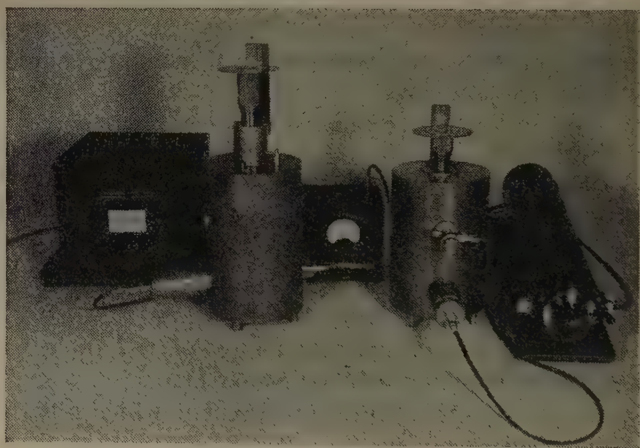


Fig. 3—Measuring apparatus for use at 200 megacycles. Left to right: galvanometer, measuring cavity, microammeter, cavity wavemeter, oscillator.

A single resonant cavity of this sort can be operated over a frequency range of 1.0 to 1.5 times the lower frequency, using a practical value of capacitance in the space where the dielectric is placed. Several different-sized cavities are thus necessary to measure dielectrics over the entire frequency range 50 to 1000 megacycles.

III. Description of Apparatus

The apparatus in Fig. 3, which operates in the frequency range of 150 to 300 megacycles, has been used by the authors for some time. Another apparatus exactly

like this one except that the cavity and wavemeter are scaled down in size is in use in the frequency range of 400 to 600 megacycles. Equipment to operate at higher and lower frequencies is planned. This equipment is convenient to use and requires little space. An advantage of this method over the coaxial-line method used by other experimenters is the small disk-shaped sample required and the ease of preparing the sample for measurement. The sample required is 1.5 inches or less in diameter and from 0.05 to 0.25 inch thick. Such a piece of material may be readily molded, cast, or machined, in the laboratory. The simple shape of the sample is of particular advantage in the case of ceramics.

Fig. 4 is a schematic circuit diagram of the setup shown in Fig. 3. The power supply which is mounted

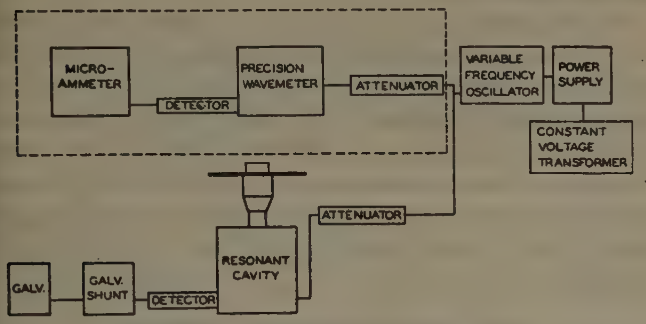


Fig. 4—Arrangement of apparatus for measurement of dielectric properties by the wavemeter method.

elsewhere is not shown in the picture. It is energized from a constant-voltage transformer. The power supply is a conventional voltage-regulated supply delivering a maximum plate current of 80 milliamperes at 450 volts and a filament current of 3.65 amperes alternating current at 2 volts. The oscillator shown is a commercial model made by a well-known radio manufacturer. Its frequency is continuously variable from 150 to 600 megacycles. We have also constructed another oscillator which proved satisfactory. The attenuators shown in the circuit of Fig. 4 are required so that any change taking place in either the cavity or wavemeter will not affect the frequency of the oscillator. From 5 to 10 decibels has proved satisfactory, and since the frequency of the oscillator must be varied in making the measurement, attenuators which are frequency-insensitive are required. Because it is difficult to design and construct attenuators which are frequency-insensitive at this frequency, it was decided to use long lengths of high-loss cable. Such long cables are frequency-insensitive since they always present their characteristic impedance to the oscillator. Coils of this cable were hung on the back of the table and, therefore, did not show in Fig. 3. The re-entrant resonant cavity in which the material to be measured is placed is shown in Figs. 5 and 6.

The exciting loop is made small and placed near the bottom where the current is a maximum. A small loop is used both to keep the Q high and to couple in only a small amount of energy. A strong field across the sample

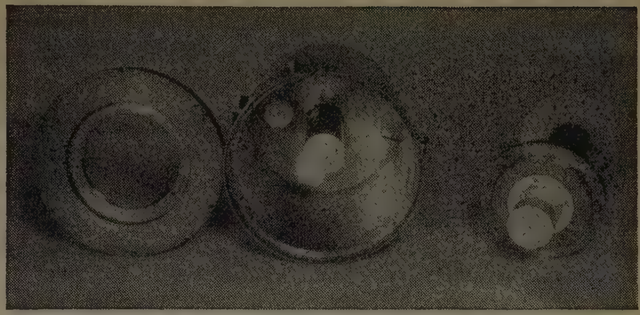


Fig. 5—Interior view of the measuring cavity for use at 200 megacycles. This cavity is 10 inches long and 6 inches in diameter.

is not desired, because it is desired to avoid all heating of the sample. To determine the dielectric constant, the empty cavity must be tuned to the frequency to which the cavity with the sample between the electrodes was tuned. This is accomplished by varying the gap between the electrodes. Therefore, fine adjustment of this gap is required. This adjustment is obtained by means of the differential screw assembly shown in Fig. 7.

To insure a positive contact all slide contacts are eliminated and a Sylphon bellows is used to connect the movable electrode with the top of the cavity. The face of the moving electrode is held rigid and parallel to the fixed electrode by the differential screw assembly (Fig. 7).

The wavemeter is constructed exactly the same as the cavity of Fig. 6, all dimensions being the same, except that the differential screw assembly is shorter since not as great a travel of the top electrode is required.

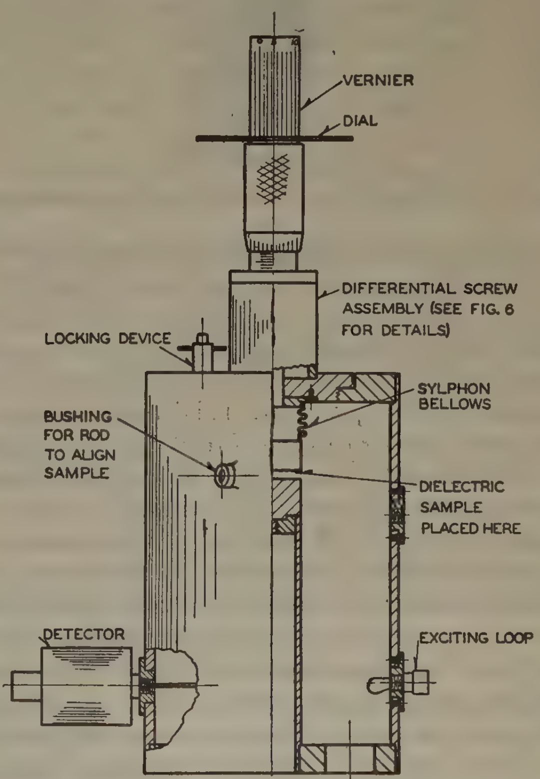


Fig. 6—The re-entrant cavity for measuring dielectric properties of materials.

Although any wavemeter capable of the required precision may be used, a wavemeter exactly the same as the cavity eliminates the need of a calibration curve. A slightly different method of coupling was used. A probe near the top of the cavity excites the cavity. This results in a higher Q than is obtained in the case of the other cavity. The Q of the wavemeter is about 4000. This is desirable because the wavemeter should tune as sharply as possible.

When the wavemeter is tuned to resonance, a very intense field is set up between the two electrodes forming the re-entrant portion of the cavity, therefore, this de-

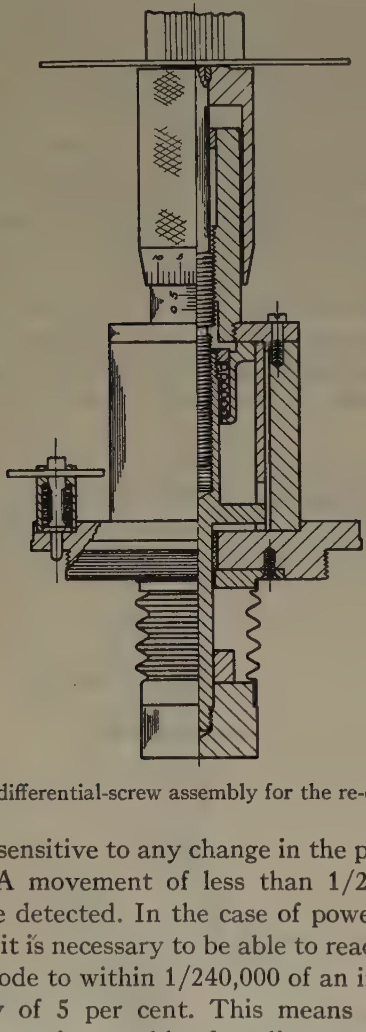


Fig. 7—The differential-screw assembly for the re-entrant cavity.

vice is very sensitive to any change in the position of the electrodes. A movement of less than 1/240,000 of an inch may be detected. In the case of power factors less than 0.0003 it is necessary to be able to read the position of the electrode to within 1/240,000 of an inch to obtain an accuracy of 5 per cent. This means a fine-thread screw and a vernier capable of reading a very small part of a turn must be used. Since all backlash should be removed from this screw, it is necessary to load it with a spring and since it is desirable to avoid using a very fine thread, a differential screw was used having screws with 20 threads per inch and 24 threads per inch which is equivalent to a screw of 120 threads per inch. The vernier dial on this assembly reads 1/2000 of a turn which gives the position of the electrode to 1/240,000 inch.

The detector units for the wavemeter and cavity consist of two crystals in parallel connected to a probe. These crystals act as a full-wave rectifier. The detector assembly was designed to keep all shunt capacitance very small so that the detector is frequency-insensitive over a wide range of frequencies. The radio-frequency current is by-passed by large capacitors built into the detector housing. The crystals operate on such a portion of their characteristic curve that the rectified current measured by an indicating instrument connected to the detector reads a current proportional to E^2 in the cavity. The length of the probe which projects into the cavity may be varied without disturbing the electrical circuits of the detector. Other types of detectors, such as a diode, bolometer, or thermocouple may be used. A diode requires a power supply and is less sensitive and less stable than a crystal. It is also more frequency-sensitive and not as compact. The sensitivity of a bolometer or thermocouple is not nearly as good as that of a crystal, and their use requires a bridge circuit of either the balanced or unbalanced type.

The detector in the wavemeter is connected directly to a microammeter, while the detector in the cavity in which the sample is placed is connected to a sensitive galvanometer (Rubicon No. 3402 H.H., sensitivity 0.005 microampere per millimeter) through a shunt. The galvanometer shunt is a ladder network so arranged that the crystal always sees the same impedance regardless of which shunt is in use and the critical damping resistance is always across the galvanometer.

IV. Calibration of Apparatus

If the dissipation factor of the cavity without the sample is known for all positions of the electrode, the work of measuring is cut in half. Therefore, it is advisable to obtain a curve of dissipation factor of the cavity without sample versus position of the electrode. Since the method of obtaining the dissipation factor of the empty cavity is the same as that of obtaining the dissipation factor of the cavity with the sample in place, this will be treated under measurements. A further advantage is that once the dissipation factor of the cavity without the sample is known, the entire measurement may be made at the resonant frequency by the "voltage method" (see (13)).

The dissipation factor of the 200-megacycle cavity without a sample was found to be nearly constant for all separations of the electrodes. To obtain the dielectric constant, we must apply two correction factors. For (2) we must obtain the value of $(C_{a2}+C_{e2})-(C_{a1}+C_{e1})$ and $(dC/dS)\Delta S$. C_{a1} is calculated from the geometry of the electrodes. The value of $(C_{a2}+C_{e2})-(C_{a1}+C_{e1})$ is obtained from the curve of capacitance versus separation of the electrodes as measured on an audio-frequency bridge. Due to stray capacitance in the circuit which could not be accurately determined, the absolute value of the capacitance between electrodes could not be measured, but the value of capacitance by difference was obtained for various separations of the electrodes, which is expressed by $(C_{a2}+C_{e2})-(C_{a1}+C_{e1})$. The fringing correction $(C_{e2}-C_{e1})$ has been found to be about 1 per cent or less with $1\frac{1}{2}$-inch electrodes used in the 200-megacycle cavity shown in Fig. 6.

The value of $(dC/dS)\Delta S$ in (2) is obtained from a

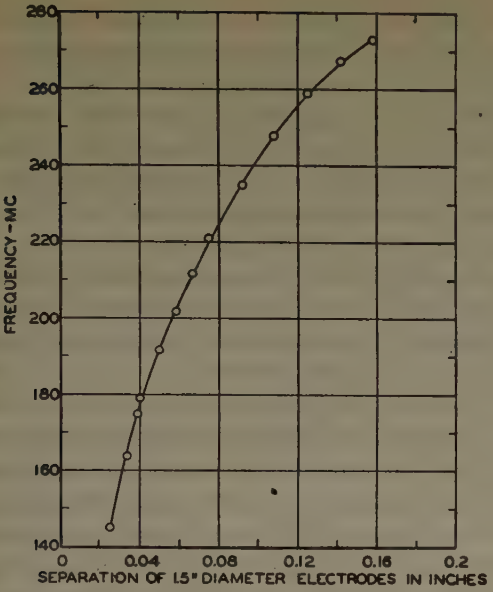


Fig. 8—The relation between resonant frequency and the separation of the electrodes of the cavity. (200-megacycle cavity used in this research.)

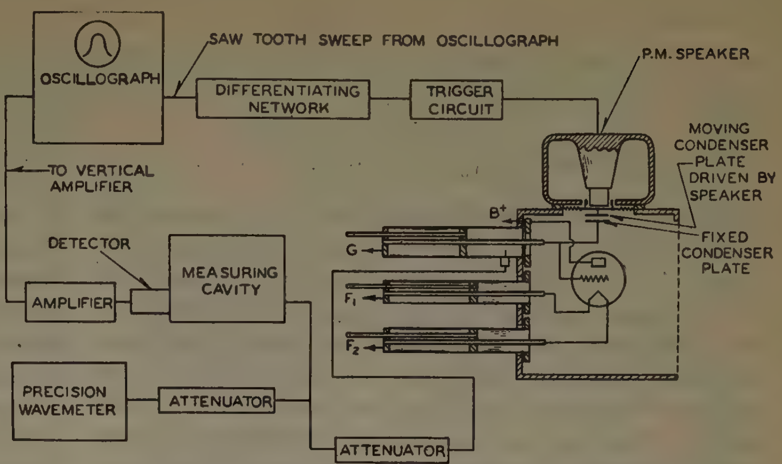


Fig. 9—Arrangement of apparatus for measuring dielectric propertie of materials by the frequency-modulation method.

curve of ΔC versus ΔS, where $\Delta C=(dC/dS)\Delta S$, and ΔS is the change in S, the length of the inner conductor, when the sample is removed and the cavity is again tuned to resonance at the same frequency. Such a curve is calculated from (4) for each value of f. By choosing values of f at convenient intervals over the frequency band covered by the cavity, a family of curves is obtained as shown in Fig. 2. Interpolating between curves, the value of ΔC corresponding to ΔS may be found for any frequency at which a measurement is made.

The resonant frequency versus electrode separation of the empty 200-megacycle cavity is shown in Fig. 8. Since the wavemeter that was used in these measurements is identical with the measuring cavity, Fig. 8 is also the resonant-frequency-versus-electrode-separation characteristic of the wavemeter. The wavemeter provides the data from which tan δ_x is calculated, and also indicates the frequency at which the measurements are made. This curve was obtained by heterodyning the oscillator which excites the cavity with a signal generator or oscillator whose frequency is accurately known and measuring the beat frequency by a suitable device. If the wavemeter were not identical to the measuring cavity, then a curve of wavemeter reading versus electrode separation of the cavity when both were tuned simultaneously to the same frequency would be required.

The crystal response was checked and found to obey the square law for the crystal current magnitude used in the measuring equipment.

V. Methods of Measurement

Wavemeter Method

With the apparatus arranged as shown in Fig. 4, the top of the cavity is removed and a disk of dielectric material is placed between the electrodes. The sample has the same diameter as the electrodes or less. It may be from 1/20 to $\frac{1}{4}$ inch thick. A locking device assures that the top of the cavity is always replaced in the same position. The sample is centered between the electrodes by means of three rods which extend through equally spaced bushings in the side of the cavity. After the sample has been centered, the rods are withdrawn from the cavity. The top electrode is then brought in contact with the sample or, in the case of samples that are easily compressed, a known air gap is left in series with the sample. D_1 is designated as the separation of the electrodes, when the sample is in place as above.

The frequency of the oscillator is varied until the resonant frequency (maximum response) of the cavity is found, and the wavemeter is tuned to this frequency and its reading noted. Then, the frequency of the oscillator is varied until the response of the cavity is reduced to half; the wavemeter is tuned to this frequency and its reading noted. A corresponding measurement is made on the other side of the resonant frequency. The oscillator is set at the resonant frequency, and the sample is removed from the cavity. The cavity is retuned to resonance and the electrode separation D_2 is noted. Unless a curve of dissipation factor of the cavity versus separation of electrodes has been obtained previously, the procedure of detuning to half power given above for the cavity with the sample in place must be repeated for the cavity with the sample removed.

In the case when the sample fills the entire space between electrodes, the dielectric constant

$$\epsilon' = C_x/C_a \tag{8}$$

where C_x is found from (2) and C_a is the calculated air capacity of the sample. A rough value of ϵ' may be obtained from the relation

$$\epsilon' = D_1/D_2 \tag{9}$$

which is simply the ratio of the electrode separations with and without the sample. This approximate expression usually gives the dielectric constant to within 5 per cent but may be in error by as much as 10 per cent.

The dissipation factor tan δ_x is given by (6c). In (6c), we may place

$$\Delta C_1/2C_x \cong (D_1' - D_1'')/2D_2 \quad (10)$$

and
$$\Delta C_2/2C_x \cong (D_2' - D_2'')/2D_2. \quad (11)$$

Then from (6c), (10), and (11),

$$\tan \delta_x \cong \frac{D_1' - D_1''}{2D_2} - \frac{D_2' - D_2''}{2D_2}. \quad (12)$$

Since only the electrode separations are required to solve this equation, it is a very convenient and rapid means of determining the dissipation factor of a sample.

The approximations for ΔC_1 and ΔC_2 in (10) and (11) introduce errors that are usually well within the precision with which D_1', D_1'', D_2', and D_2'' may be read, especially when measuring low-loss material. It should be noted that ΔC_1 and ΔC_2 are the differences of nearly equal quantities. However, when materials having high loss are being measured, and ΔC_1 is large, the terms $C_{e1}-C_{e2}$ and $(dC/dS)\Delta S$ of (2) may be large. Then ΔC_1 should be found in the same way that C_x is found from (2).

Since it is not possible to prepare all samples so that their opposite faces are absolutely parallel or the surfaces perfectly smooth, there is an air gap between the electrodes and sample when the electrodes are brought into contact with the sample. The effect of this unavoidable air gap may be minimized in either of two ways. If it is possible to determine the size of the sample accurately, an air gap of known dimension may be placed in series with it. This method has the serious disadvantage, especially in the case of low-loss materials, of reducing the sensitivity of the measurement so that it may still be impossible to obtain the desired accuracy. The other way of minimizing the effect of irregularities in the sample is to place a thin metal foil of soft material over each face of the sample. This has been done at lower frequencies, and was used in measurements in the 150- to 300-megacycle range. Correction for the losses in the foil is made according to the method of Hartshorn.[15]

Heterodyning Method

The construction of a precise wavemeter involves considerable precision machine work, and is, therefore, an expensive operation. Therefore, it may be desirable to eliminate the wavemeter from the apparatus and this eliminates the equipment shown inside the dotted line of Fig. 4. This can be done if the following equipment is available: A calibrated oscillator or signal generator whose frequency or harmonics fall in the required band, a mixer (usually a crystal), and a calibrated receiver or other suitable detector. The frequency of this signal generator must be stable and its frequency known to the precision desired for the value of $\tan \delta_x$.

The frequencies at the half-power points (f_1', f_1'') and at resonance (f_1) of the measuring cavity with the sample in place are determined by beating the varied frequency of the oscillator feeding the measuring cavity against the fixed frequency of the second oscillator or signal generator. The two oscillator frequencies are fed through a crystal mixer into a calibrated receiver which measures their beat frequency or difference frequency. The capacitances C_1' and C_1'' (between the electrodes in the cavity) necessary to produce resonance at f_1' and f_1'' are then found after the sample has been removed. The frequencies at the half-power points (f_2', f_2'') and at resonance (still f_1) with the sample removed are found by the same procedure. These correspond to capacitances C_2' and C_2''. Calculation of $\tan \delta_x$ then proceeds according to (6c) or (10) to (12).

There are several disadvantages to this method of measuring the frequency which make it more time-consuming than measurement by means of a wavemeter. If there is any instability in one of the elements, it is difficult to determine which one is unstable, making adjustment tedious. At higher frequencies when a signal generator is used, it becomes difficult to locate the beat frequencies and finally, a suitable receiver, if not already at hand, is an expensive instrument.

Frequency Modulation Method of Determining the Dissipation Factor of a Dielectric Sample Using an Oscillograph

With the equipment arranged as in Fig. 9, the saw-tooth wave from the sweep oscillator in the oscillograph is applied both to the horizontal deflecting plates and to a trigger circuit. The output of the trigger circuit, which is the derivative of a saw-tooth wave, is fed to a phase-modulation loudspeaker, an integrating device. A speaker with the cone removed was mounted on the frame of a coaxial-line ultra-high-frequency oscillator, similar in construction to one described by Barrow.[16] The movement of the speaker diaphragm rod varies the capacitance in the grid circuit of the oscillator, and therefore, varies the frequency by a small amount. The oscillator delivers a signal which is frequency-modulated in accordance with the saw-tooth sweep applied to the horizontal plates of the oscillograph. The modulated output of the oscillator is fed to a precision wavemeter and to the cavity containing the dielectric sample. The resonant cavity changes the frequency-modulated signal into an amplitude-modulated signal so that a resonance curve appears on the screen of the oscillograph.

When the precision wavemeter is tuned to the resonant frequency of the cavity, a pip appears on the resonance curve on the oscillograph screen due to the absorption of power by the wavemeter. By adjusting the gain controls of the vertical and horizontal amplifiers, the resonance curve of the cavity is made to coincide with the universal resonance curve drawn on the screen of the oscillograph with its half-power points marked with vertical lines. The bandwidth of the resonance curve can now be measured by running the wavemeter

[15] L. Hartshorn, "Radio-frequency measurements by bridge and resonance methods," John Wiley and Sons, New York, N. Y., 1941, pp. 198–200.

[16] W. L. Barrow, "Oscillator for ultra high frequencies," *Rev. Sci. Instr*, vol. 9, pp. 170–174; June, 1938.

pip along this curve from one vertical line to the other. By noting the dial reading of the wavemeter when the pip coincides with each vertical line in each case (i.e., sample in place and removed) the same formulas given in a previous section of this paper may be used to obtain the dissipation factor of the dielectric tan δ_x.

The chief difficulty encountered in using this method is that the bandwidth of the cavity is so narrow and the wavemeter pip of such considerable width in comparison that it is impossible to obtain an accurate measurement of the bandwidth. The same difficulty occurs to a lesser extent in the case of the cavity with the sample in place. However, it is possible to raise the Q of the wavemeter considerably and to lower the Q of the measuring cavity. This should overcome this difficulty. When this equipment is working properly, measurements may be made much faster than when using the first method described (varying the frequency manually to reduce the response to half on each side of resonance). However, it is not as fast or convenient as the voltage method.

Another disadvantage is the fact that introducing a capacitance into the grid circuit of the oscillator lowers its frequency so that it must be designed for a much higher frequency when its signal is modulated in this way. Also, in the case of high-loss material, it is difficult to modulate enough to obtain a sufficient portion of the resonance curve to make measurements.

Voltage Method

In this method the sample is placed in the cavity, the oscillator tuned to resonance, and the galvanometer reading noted. Then the sample is removed from the cavity and the cavity tuned to resonance, the frequency remaining constant, and the galvanometer reading noted. The dielectric constant may be calculated in the usual manner, and the dissipation factor tan δ_x is calculated from

$$\tan \delta_x = [(V_0 - V_T)]/V_T(\Delta C_2/2C_x). \quad (13)$$

It should be recalled that $\Delta C_2/2C_x$ is the dissipation factor of the empty cavity and its value is obtained before any measurements are made on samples as explained in the section on Calibration of Apparatus. When the expression $(V_0 - V_T)/V_T$ is less than unity, the absolute accuracy obtained is better than that of the other methods.

Since this method is much faster and more convenient than the others, it is preferred in most cases by the authors. The time required to make a measurement is practically the time required to place the sample in the cavity and then remove it, as the sample need remain only long enough to read the galvanometer deflection. If the apparatus is to be used in the routine testing of samples that have similar dielectric properties, a wavemeter is not needed. However, if the apparatus is to be used in the laboratory to test materials having a wide range of dielectric properties, the use of a wavemeter is recommended.

VI. Representative Measurements of Dielectrics

The results of the measurement of a few typical dielectrics are given in Table I. The power factor of these materials varied from 4.7 to 0.01 per cent. These samples also varied considerably in thickness. The measurements of various thicknesses of Sample A of polystyrene shows that the measurements are independent of the thickness of the sample. Samples were desiccated previous to measurement.

TABLE I

Typical Results of Measurements of Dielectric Properties at About 200 Megacycles

Material	Thickness of sample inches	Dielectric Constant	Dissipation Factor
Micarta No. 254 {Cresol-formaldehyde Resin paper filled}	0.150	3.72	0.047
Columbia Resin CR-39	0.149	2.96	0.027
Pure fused Quartz	0.206	3.79	0.0001
Polystyrene Sample A	0.150	2.55	0.0003
Polystyrene Sample A	0.100	2.565	0.0003
Polystyrene Sample A	0.250	2.56	0.0003
Polystyrene Sample B	0.151	2.56	0.0005
Polyvinyl Carbazole	0.115	3.06	0.0009
Special Styrene Copolymer	0.183	2.64	0.008
High-Tension Porcelain	0.186	5.90	0.010
Zircon Porcelain	0.178	9.5	0.0008
Ultra Steatite	0.215	5.23	0.0007
Steatite	0.247	5.45	0.0034

VII. Accuracy of Method

The accuracy obtainable in this re-entrant cavity method of measurement is about ± 0.00005 in tan δ_x and about ± 1 per cent with optimum-size sample, in dielectric constant. The sensitivity or accuracy of the re-entrant cavity as used in this method of measurement is limited largely by the precision and sensitivity of changing, and measuring the change in separation and absolute separation of the electrodes.

The accuracy of the dissipation factor measurement rests upon the assumption that extension of the bellows with a fixed frequency in the cavity does not change the Q of the cavity. This assumption was substantiated by test measurements. The movement of the bellows is never more than $\frac{3}{16}$ inch and usually less than $\frac{1}{8}$ inch. Measurement of the Q of the empty cavity varies only slightly with frequency (obtained by changing the gap separation), almost within the precision of measurement, and within the predicted theoretical change.

The accuracy of all the dielectric-loss measurements described in this report depends upon the assumption that the universal resonance curve holds for our cavity as arranged with the coupling loop and feeding line. In other words, the voltage variations in the cavity are assumed to correspond to frequency changes of the oscillator source according to the resonance curve of the cavity, and are independent of coupling elements. The response of the cavity, has been checked with the universal resonance curve and close agreement obtained.

Conclusion

A new method for measuring the dielectric properties of insulating materials in the 100- to 1000-megacycle range has been developed. The theory and several

methods of operation are described. The theory on which this method is based has been justified experimentally. Greater sensitivity and accuracy have been obtained than is possible by other methods operative in this frequency range. This method offers the following advantages:

(1) The samples required are of simple disk shape which are easily prepared. (2) Both the measurements and the calculations are simple, making possible rapid determinations of both dielectric constant and power factor. (3) These characteristics make the apparatus not only suitable for laboratory use but also for production control where a relatively large number of samples may be involved.

A Note on Diode Modulation*

A. D. BAILEY†, ASSOCIATE, I.R.E., AND G. H. FETT‡

Summary—**An analysis of a circuit using the diode as the modulating element is given. The theoretical relations derived for a resistance load are verified experimentally. The effect of using a tuned circuit as a load is discussed and the experimental results are explained in terms of a variable diode resistance.**

WHILE the applications of diode modulation are not as numerous as other methods of producing amplitude modulation, there are certain advantages in its use in certain types of carrier telephone equipment and in instruction. This note gives experimental verification for the diode-modulation relations obtained theoretically for a resistance load. The effect of replacing the resistance load by a resonant circuit tuned to the carrier is described and an explanation is given on the basis of a variable diode resistance.

Resistance Load

The diode rectifier current-voltage characteristic will be assumed to be ideal; the diode resistance is infinite for negative values of voltage, and zero for positive values of voltage. This diode is connected in series with a resistance load, a direct biasing voltage, and a sinusoidal carrier voltage. Let the magnitude of the biasing voltage be varied. When the bias voltage tends to make the diode plate negative the plate current will flow only a part of the cycle. The fraction of a cycle during which the tube conducts, expressed in radians referred to the carrier voltage, is called the conduction angle. The conduction angle depends upon the ratio of bias voltage to carrier voltage. The magnitude of the conduction angle of the diode will determine the magnitudes of the harmonic components of the carrier voltage appearing across the load, as well as that of the fundamental frequency. The bias voltage may be replaced by the low-frequency modulating signal. Therefore, an analytic relation between conduction angle and amplitude of the fundamental frequency load voltage is important.

Let E_p represent the amplitude of the carrier at the source, E_{bb} the bias voltage, $\cos\alpha = -E_{bb}/E_p$ the cosine of half the conduction angle, and H_1, H_2 and H_3 represent the amplitudes of the carrier (fundamental), second-, and third-harmonic voltages across the load. Then it may be shown that[1]

$$\frac{H_1}{E_p} = \frac{\alpha - \sin\alpha\cos\alpha}{\pi}$$

$$\frac{H_2}{E_p} = \frac{1}{\pi}\left[\frac{\sin 3\alpha}{3} + \sin\alpha - \sin 2\alpha\cos\alpha\right]$$

$$\frac{H_3}{E_p} = \frac{1}{\pi}\left[\frac{\sin 4\alpha}{4} + \frac{\sin 2\alpha}{2} - \frac{\sin 3\alpha\cos\alpha}{1.5}\right].$$

In Fig. 1 are plotted the predicted magnitudes of the harmonics to be obtained for an ideal diode. It is seen that the magnitude of the fundamental varies linearly with the ratio of bias to carrier voltage, indicated by the straight line AB in the range of bias values $-E_p/2 < E_{bb} < E_p/2$. (Negative values of E_{bb} are important when the modulating signal is correspondingly negative.) If the direct-current bias is replaced by a modulating signal, then in the range specified linear modulation will take place.

When the theoretical relation experimentally is tested allowance must be made for the finite diode resistance during conduction which reduces the output voltage in the ratio of $R_b/(r_p+R_b)$ where r_p is the alternating-current tube resistance and R_b is the load resistance. Experimentally obtained curves for a 6H6 diode in

[1] For a derivation of the first term see H. J. Reich, "Theory and application of electron tubes," McGraw-Hill Book Company, New York 18, N. Y., 1939, p. 122. The other terms may be derived in exactly the same way. The voltage across the load may be written directly as $e = E_p(\cos\omega_p t - \cos\alpha)$. Expansion of the right-hand side of the equation into a Fourier series

$$e = H_0 + H_1\cos\omega_p t + H_2\cos 2\omega_p t + H_3\cos 3\omega_p t + \cdots$$

gives the expressions for the equations for H_2 and H_3. Thus

$$H_2 = \frac{1}{\pi}\int_0^{2\pi} e\cos 2\omega_p t\, d(\omega_p t)$$

$$= \frac{E_p}{\pi}\int_0^{2\pi}(\cos\omega_p t - \cos\alpha)\cos 2\omega_p t\, d(\omega_p t)$$

and similarly for H_3,

$$H_3 = \frac{E_p}{\pi}\int_0^{2\pi}(\cos\omega_p t - \cos\alpha)\cos 3\omega_p t\, d(\omega_p t)$$

* Decimal classification: R135. Original manuscript received by the Institute, September 29, 1944; revised manuscript received, December 6, 1944.

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eries with a 1000-ohm resistive load connected in series vith a low-impedance 60-cycle source and a variable lirect-current bias are shown in Fig. 2. (The low carrier requency was chosen because harmonics of the fundamental could then be measured accurately with the wave-analysis equipment available. It also provided a ow impedance to the important harmonics in the output.) The similarity between these curves with those of Fig. 1 is striking.

In the curves of Fig. 2 the actual load-voltage frequency components are plotted. The expressions which have been derived assume no internal diode resistance.

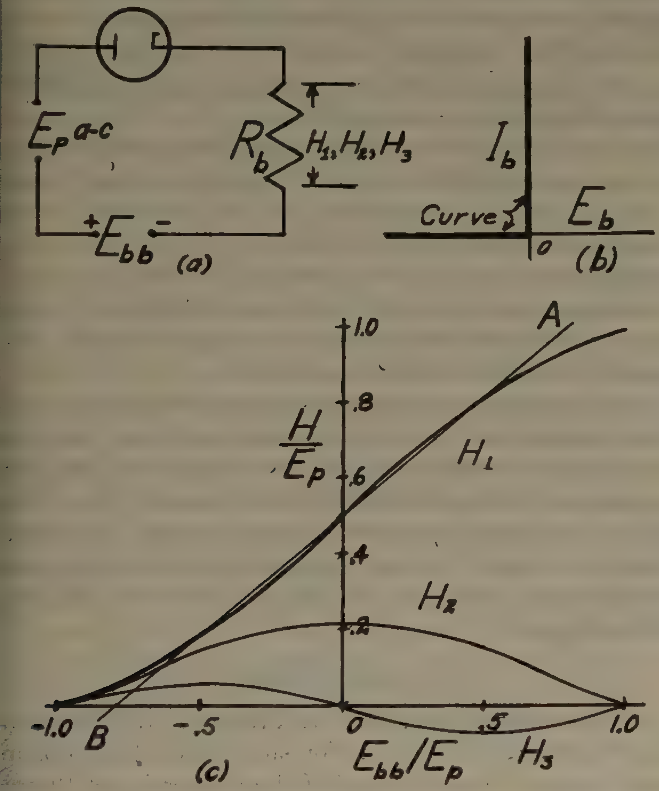


Fig. 1—Ideal diode response.
(a) Circuit to be used. (b) Ideal diode characteristic. (c) Harmonic-voltage components across load resistance as function of bias voltage.

If the experimentally obtained curve for H_1 is multiplied by the ratio $(r_p+R_b)/R_b$ it should give a curve identical to that for H_1 in Fig. 1. The comparison is shown in Fig. 2. Since r_p is not constant, the use of an average value will cause some error. The agreement shown in Fig. 2, and similar curves which can be obtained for H_2 and H_3 lead to the conclusion that the derived expressions for an ideal diode with no internal resistance may be modified for the practical problem by multiplication of the expressions for H_1, H_2, H_3 by the fraction $R_b/(r_p+R_b)$ to obtain the actual load-voltage components.

Tuned-Circuit Load

It might be thought that for a diode modulator terminated with a parallel resonant circuit the response for the fundamental frequency would be the same as

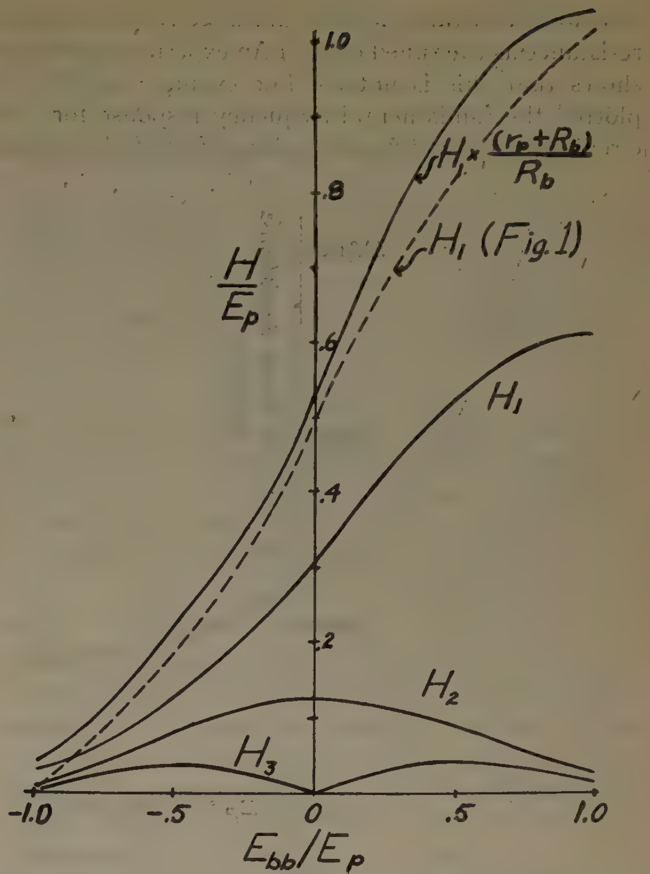


Fig. 2—Experimental diode response for circuit of Fig. 1 (a). Harmonic-voltage components observed, as functions of bias voltage. (Equipment available could not measure phase shift of H_1.)

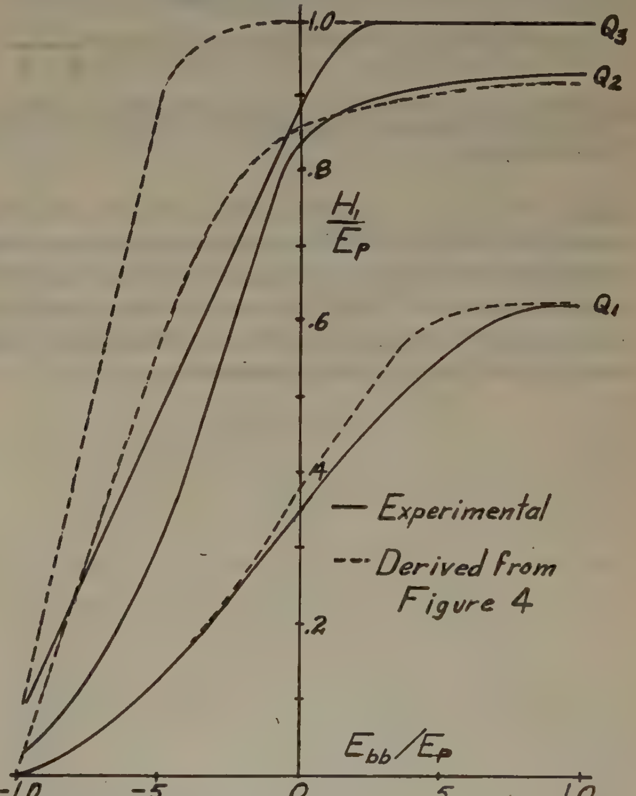


Fig. 3—Experimental diode response for tuned-circuit load. Constants adjusted to $Q_1=9.2$, $Q_2=29.5$, and $Q_3=74.5$ (solid lines). Computed diode response with apparent diode resistance derived from Fig. 4.

that for a resistance load of the same carrier-frequency resistance as the tuned circuit. An experimental analysis shows that this is not so. For example, in Fig. 3 is plotted the fundamental-frequency response for tuned circuits for three different values of Q of the parallel-

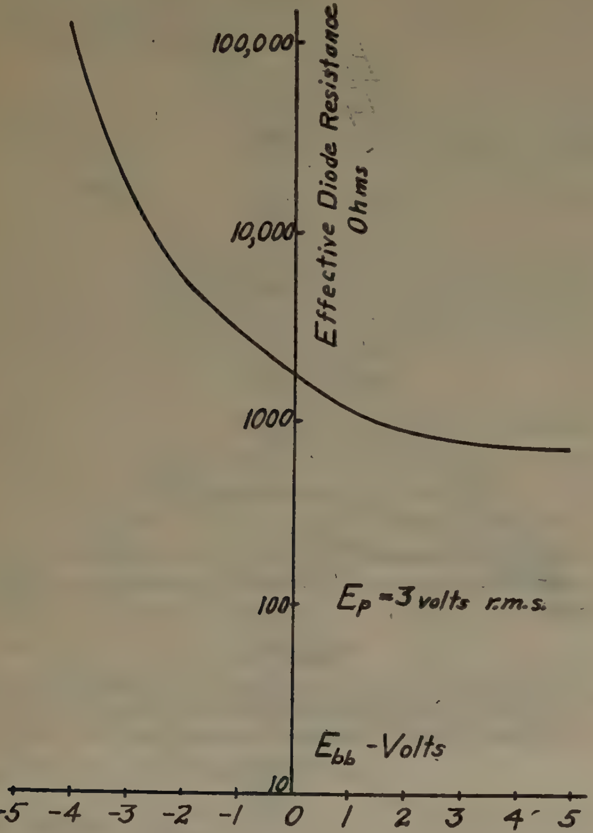


Fig. 4—Apparent effective diode resistance of 6H6 tube with constant-carrier voltage of 3 volts (root-mean-square) as a function of bias voltage.

resonant circuit. It is seen that for circuit 1, with the lowest Q of 9.2 the curve is not too different from what would be predicted for a resistance load. The curves for circuit 2 with a Q of 29.5 and circuit 3 with a Q of 74.5, however, have response curves which differ greatly from those obtained with a similar resistance load.

Since the magnitude of the fundamental does not i crease when the bias ratio is positive, (for high valu of Q) it is suggested that the diode is actually operati as a variable resistance in series with the load and t source, the magnitude of the resistance dependent upo the value of the negative-bias voltage. Now the a parent effective resistance of the diode may be define as the ratio of the effective voltage across the diode the effective current in the diode. The effective value the diode voltage is the square root of the sum of t squares of the alternating voltage and the direct voltag An experimental measurement of the apparent effecti diode resistance as a function of the biasing voltage shown in Fig. 4. It is noted that the resistance is near constant at the static value of 750 ohms for positi values of bias, and that it rises rapidly to nearly 100,0 ohms for negative values of bias.

If the diode is then considered as a variable resistanc and an analysis of the circuit is made, the curves, show dotted in Fig. 3, are obtained for the amplitude of t fundamental frequency in terms of the bias. The com puted curves and the experimental curves are in fa agreement, when the difficulties of obtaining the a parent effective resistance and the high harmonic con tent for negative bias are considered.

It is seen from the considerations in this note that t diode-modulation circuit for resistance load may b treated by Fourier analysis in the formal way, and goo agreement with practice may be expected. When t load is a parallel resonant circuit, however, the dio must be treated as an apparent effective resistanc which varies with the amplitude of the modulati (bias) signal.

Acknowledgment

Acknowledgment is made to Professor H. J. Reich, o the University of Illinois, for suggesting the proble and to the Graduate School of the University of Illino for permission to publish the note, which was a part of thesis submitted for the degree of Master of Science i Electrical Engineering by the first-named author unde the direction of the second.

Experimentally Determined Impedance Characteristics of Cylindrical Antennas*

GEORGE H. BROWN†, FELLOW, I.R.E., AND O. M. WOODWARD, JR.†, ASSOCIATE, I.R.E.

Summary—Measurements of resistance and reactance of cylindrical antennas operated against ground have been made, with a wide variation of both antenna length and diameter. These data are displayed by means of a series of graphs.

The maximum values of resistance encountered are displayed. The shortening effect near the quarter-wave resonance point is also shown.

Terminal conditions, such as capacitance of the base of the antenna to ground, are briefly considered, and a series of measurements shows the wide variation in impedance for varying terminal conditions.

Measurements made in the course of the investigation show that the impedance of the antenna is independent of whether the top of the radiator is open or closed. The measured impedance data are also directly applicable to the case of a center-fed dipole.

I. Introduction

A KNOWLEDGE of the base impedance of vertical antennas as a function of antenna length and diameter is very helpful in devising terminating networks for antenna systems. Much has been written concerning the mathematical difficulties of rigorously solving the antenna problem, and several methods of approximation have been proposed. Very little information of an experimental nature has been published. A number of years ago, the writers decided to undertake a systematic investigation of the problem. Other projects of a more pressing nature have seriously impaired our plans. However, the work of measuring the resistance and reactance of simple cylinders has been completed and the data compiled. The purpose of this paper is to present these data in a form that may prove useful.

II. Method of Measurement

The physical arrangement for making the measurements is shown in Fig. 1. A large circular metallic screen 12 feet in diameter and 15 wires to the inch was placed on the surface of the earth. A concentric transmission line ran below this screen back to a slotted section of measuring line. Here a sensitive probe indicated the ratio of minimum-to-maximum voltage on the line as well as the position of a voltage minimum on the line. These two quantities together with the characteristic impedance of the feed line establish the impedance that exists at the end of the line. The inner diameter of the outer conductor of the feed line was 0.785 inch, while the diameter of the inner conductor was 0.25 inch. The cylinder which formed the antenna was closed at the bottom with a circular metal plate.

The writers rather like the method of notation which expresses dimensions in electrical degrees. For instance, in Fig. 1, the dimension a which is the physical length from the ground plane to the top of the antenna may be used to compute the length A in electrical degrees.

$$A(\text{degrees}) = 360a/\lambda \tag{1}$$

where λ is the free-space wavelength measured in the same units in which a is measured. The actual diameter d may be used in the same way to express the diameter D in electrical degrees.

Two simple and useful formulas for computing A are

$$A(\text{degrees}) = a_{\text{ft}} f_{kc}/2725 \tag{2}$$

and

$$A(\text{degrees}) = a_{\text{inches}} f_{mc}/32.7. \tag{3}$$

Measurements were made on wires and cylinders of various diameters, with D ranging from 0.1 degree to 20 degrees. This range was chosen with an eye to practical considerations, for a 3-inch diameter mast at 1 megacycle represents a value of D close to 0.1 degree, while a diameter of 1.3 inches at 500 megacycles is approximately 20 degrees.

The spacing h between the ground plane and the metal plate closing the bottom of the cylinder was chosen so that this electrical spacing H was one degree.

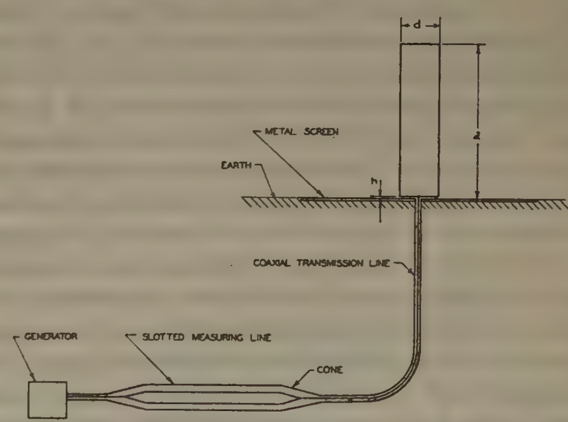


Fig. 1—Physical arrangement used in making impedance measurements.

III. Resistance and Reactance Variation, with Diameter and Frequency Constant, and the Antenna Length Variable

A complete series of measurements was made by choosing a cylinder of a certain diameter, maintaining a fixed frequency of 60 megacycles, while the physical length of the antenna was changed. The resulting resistance curves are shown in Fig. 2, while the corresponding reactance values are presented in Fig. 3.

From Fig. 2, we see that the maximum value of

* Decimal classification: R241.1×R320. Original manuscript received by the Institute, September 18, 1944; revised manuscript received, November 30, 1944.

† RCA Laboratories, Princeton, New Jersey.

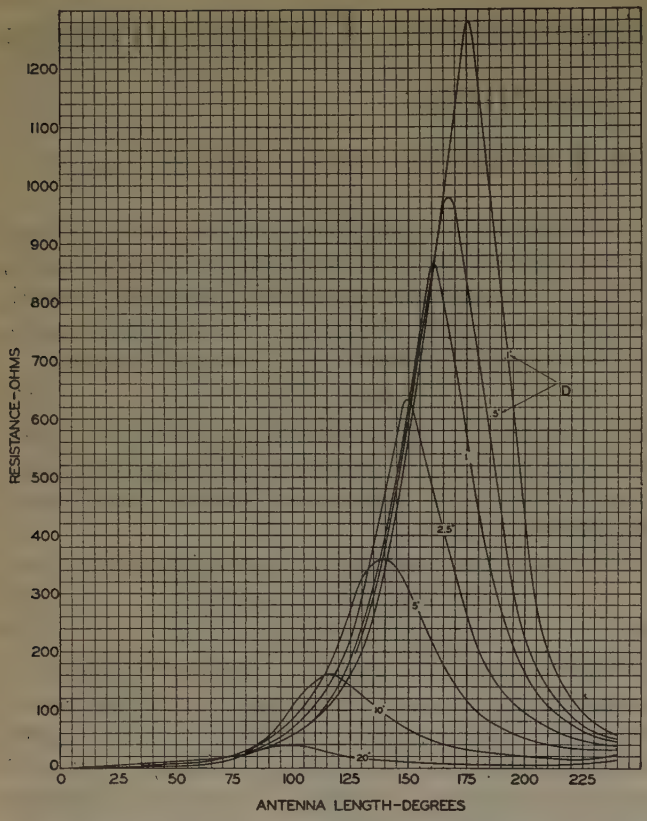


Fig. 2—Measured resistance curves versus antenna length in degrees, for a number of fixed diameters. Here the frequency is held constant and the physical length of the antenna is changed.

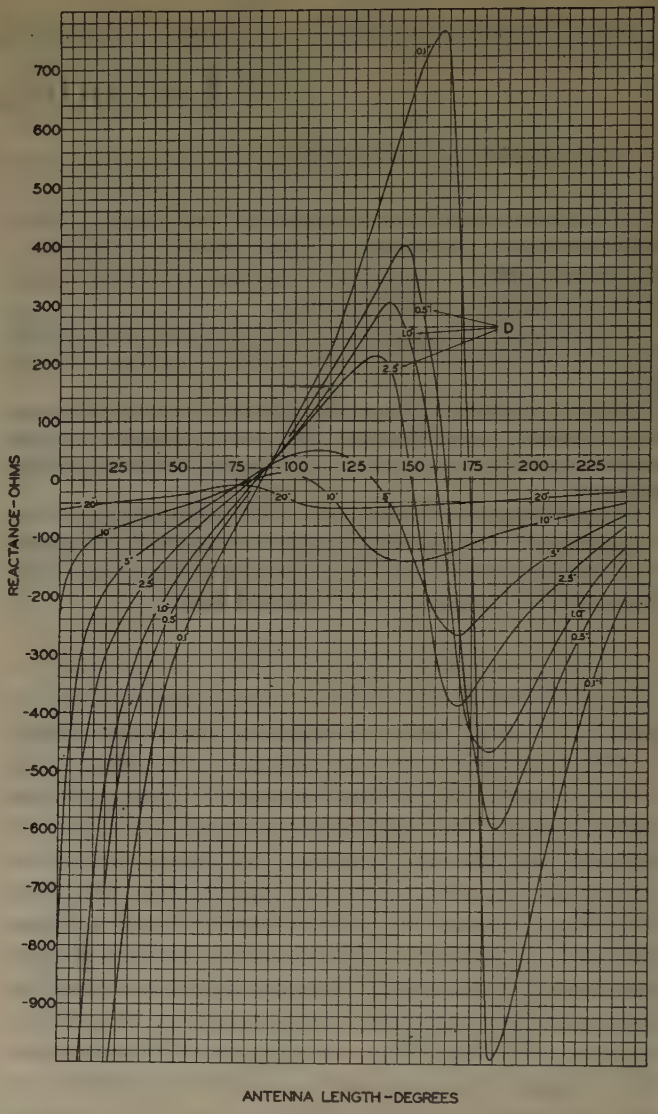


Fig. 3—Measured reactance curves versus antenna length in degrees. Again the frequency is held constant and the physical length of the antenna is changed.

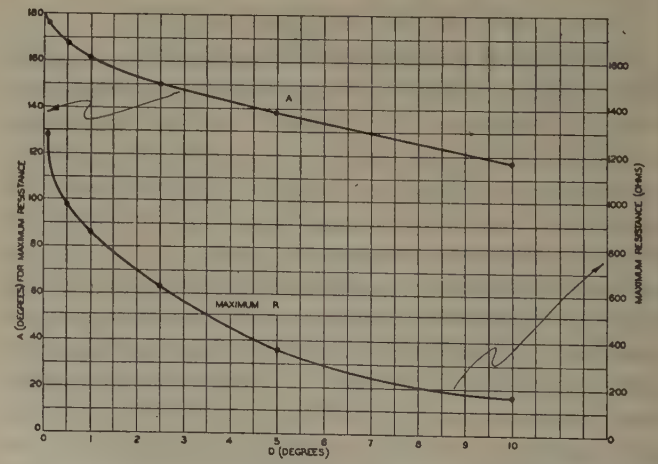


Fig. 4—Maximum resistance versus antenna diameter D and the antenna length A at which the maximum resistance occurs versus antenna diameter.

resistance for each diameter becomes greater and occurs closer to $A=180$ degrees as the diameter becomes smaller. This point is illustrated strikingly by Fig. 4. This diagram was constructed from Fig. 2. The top curve in Fig. 4 shows the antenna length A at which maximum resistance occurs for each value of D. The corresponding value of the maximum resistance is shown by the lower curve. The upper curve extrapolates very nicely and shows that as D approaches zero, for maximum resistance, A approaches 180 degrees. The lower curve shows that there is a good chance of the resistance approaching infinity as the diameter approaches zero.

Fig. 3 shows that as the antenna becomes very short, the reactance approaches a definite limiting value. The effect is particularly striking in the case where D is 20 degrees. Actually, in our measurements, the antenna length did not go down to zero degrees, for when the antenna has been trimmed entirely away, the plate which formed the bottom of the cylinder still remained, so that we measured the reactance of this disk hung on the end of the measuring line. It should be realized that all of our measurements shown in Figs. 2 and 3 are the combined impedances of the antenna proper in parallel with the base reactance. Theoreticians may well object that this prevents comparison between theoretical and experimental results. It is entirely possible to imagine a cylinder with the base removed and excited by a number of tiny generators connected between the periphery and the ground plane. Then a knowledge of the relationship between the generator voltage and the current delivered by the generators would give an answer closer to the

ideal, since the base charging current would not be present. However, a realistic consideration of the problem soon indicates that these measurements taken under true existing conditions are likely to be of more value from a design standpoint.

It might be added that the effect of this base capacitance only makes itself felt where D is larger than one degree.

It may be observed from Figs. 2 and 3, that the reactance curve crosses through zero close to the point where the resistance is maximum. There is, however, some slight departure from true correspondence. The solid curve in Fig. 5 shows the antenna length for zero reactance as a function of the diameter, D. By calculation from Figs. 2 and 3, the writers determined the zero reactance point when the base reactance was removed. The resulting values of antenna length are shown by the broken curve of Fig. 5.

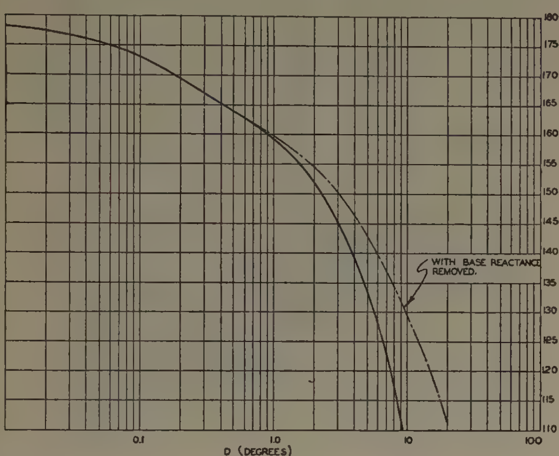


Fig. 5—The solid curve shows the antenna length A for zero reactance (near the maximum resistance point) as a function of the diameter D. This information is taken from measured data. The broken curve shows the same quantities when the base reactance is removed by calculation.

IV. Resistance and Reactance Variation, with Diameter and Length Constant, and with Variable Frequency

The curves of Figs. 2 and 3 show the impedance variation when the antenna length is varied. Often, it is of interest to know the action for a fixed antenna as the frequency is varied. By working through the curves of Figs. 2 and 3, and by cross-plotting much of the experimental data, the writers were able to build up Figs. 6 and 7. Here the resistance and reactance variation is shown for a fixed ratio of antenna length to diameter, and the variation of the electrical length of the antenna is secured by varying the frequency.

It may be noted that the reactance curves approach infinite values as the antenna length approaches zero, since the approach to zero antenna length is secured by approaching zero frequency.

Figs. 6 and 7 may prove to be useful in designing antennas to cover a wide frequency range.

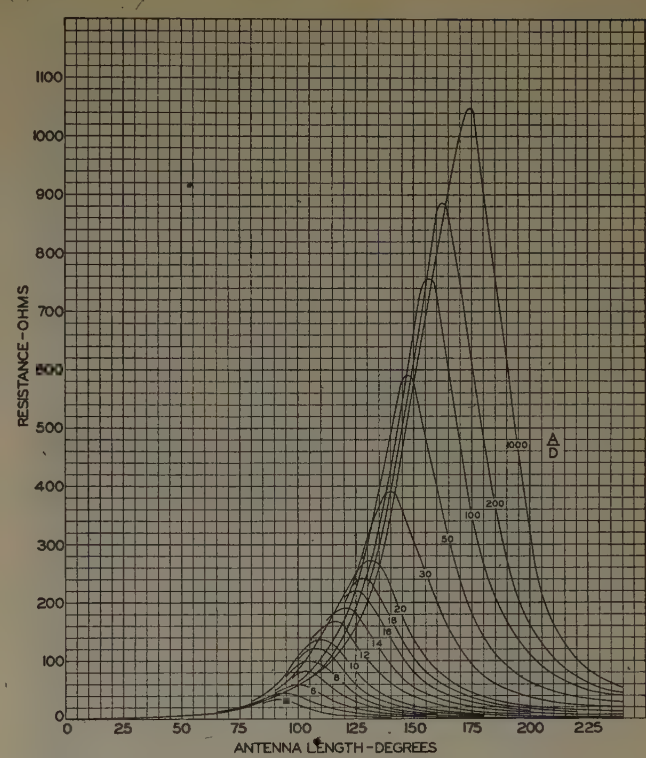


Fig. 6—Antenna resistance versus antenna length A, when a constant ratio of length to diameter A/D is maintained. Here the length and diameter are held constant while the frequency is changed.

Fig. 8 presents the data of Fig. 6 in a somewhat different fashion. Here each curve shows the antenna resistance as a function of the ratio of antenna length to diameter (A/D) for a fixed antenna length. Since the antenna length is fixed for each curve, large values of A/D represent very thin wires, while small values of A/D correspond to fat antennas. It is interesting to note that the resistance of a wire whose length A equals 90 degrees and whose A/D value is greater than 100 is very close to the theoretical value of 36.6 ohms obtained from the assumption of a simple sine-wave distribution of current.

Reactance curves as a function of A/D are given by Fig. 9. Many of these curves would be altered remarkably by removing the shunting reactance at the base, or by altering the terminal conditions.

Reference to Fig. 6 helped in the preparation of Fig. 10, where the maximum resistance as a function of A/D is shown.

Another interesting bit of information may be extracted from the data shown in Fig. 7 and Fig. 9. It is generally known that the first resonance in a vertical antenna occurs close to a length of A equal to 90 degrees, and it is also general knowledge that the antenna should be shortened slightly from the 90-degree length to obtain this resonance or zero-reactance condition. By cross-plotting the data of Figs. 7 and 9, the writers obtained Fig. 11, which shows the shortening (expressed in per cent of 90 degrees or one-quarter wavelength) necessary to secure zero reactance for each value of A/D.

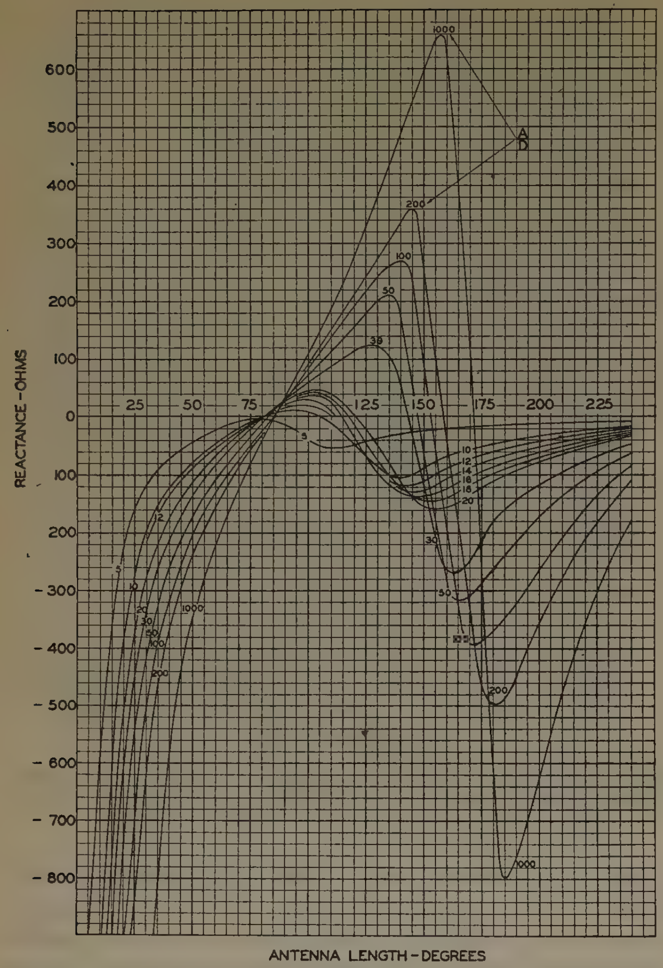


Fig. 7—Reactance curves corresponding to the resistance curves of Fig. 6.

V. Reactance of the Base-Plate

As has been stated, the disk which closes off the bottom of the radiator forms a shunt capacity across the terminals of the radiator. We may estimate the amount of the base shunting reactance by calculating the capacitance of the disk, neglecting fringing at the edges,

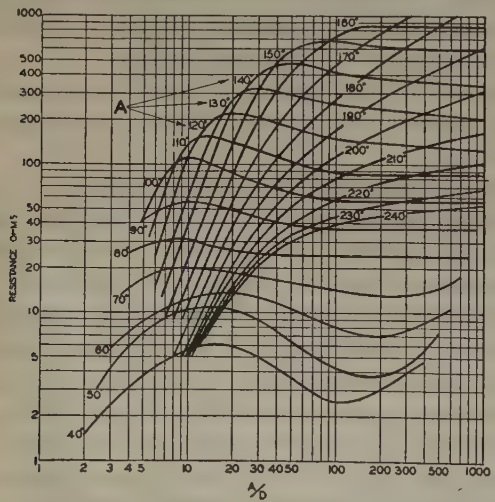


Fig. 8—Resistance versus the ratio A/D with antenna length A as a parameter.

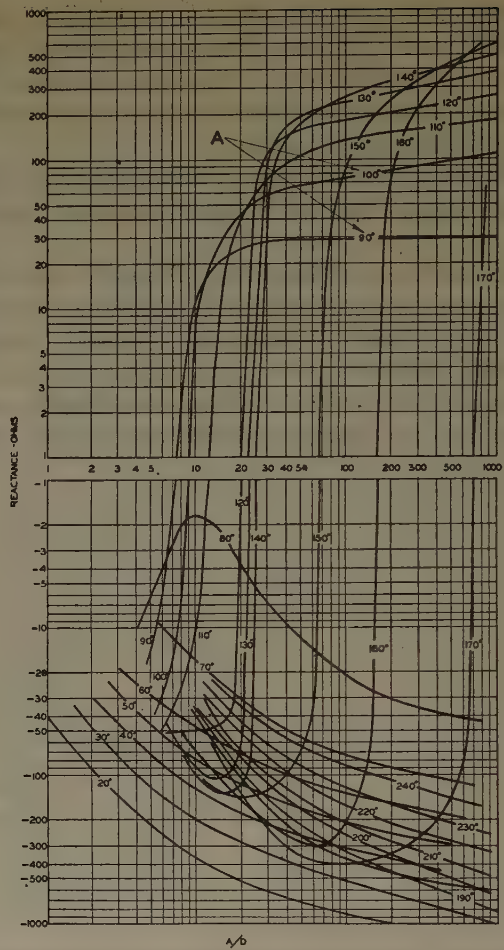


Fig. 9—Antenna reactance versus the ratio A/D for a number of values of antenna length A.

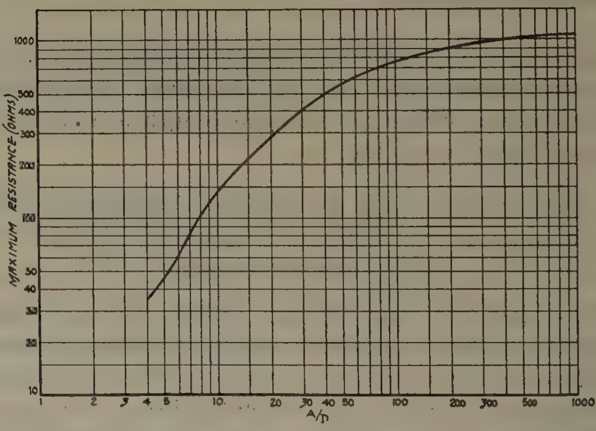


Fig. 10—Maximum resistance as a function of the ratio A/D.

and assuming that all displacement currents flow from the bottom of the disk to the ground plane. Then the shunt reactance is

$$X_s = \frac{\mu c^2 h}{\omega(\pi d^2/4)} \tag{4}$$

where μ = permeability of free space $= 4\pi \times 10^{-9}$

c = velocity of radio waves in free space $= 3 \times 10^{10}$ centimeters per second

h = spacing of disk from plane (centimeters)

d = diameter of disk (centimeters)
$\omega = 2\pi f$
f = frequency in cycles per second

Then we may rewrite (4) as

$$X_s = \frac{480(\omega h/c)}{(\omega d/c)^2}. \tag{5}$$

However, if we express the spacing in electrical degrees H and the diameter in the same way D, (5) becomes

$$X_s = 27{,}500 H/D^2. \tag{6}$$

In making the measurements shown in Figs. 2 and 3, we kept H equal to 1 degree. Thus, for D equal to 20 degrees, we see that the shunt capacitive reactance is 68.3 ohms, a quantity which is not at all negligible. However, when D is 1 degree, the shunt reactance is 27,500 ohms, a rather high value compared to any value of impedance encountered during the course of measurement.

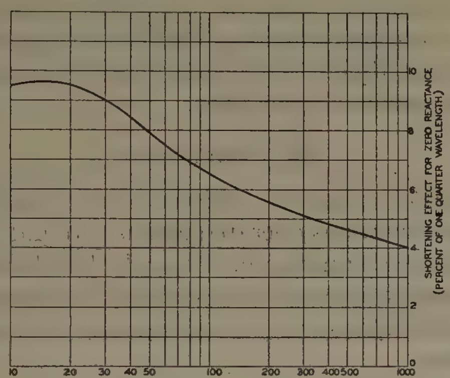


Fig. 11—Shortening effect near the quarter-wave point.

VI. Comparison of Impedance Measurements with Varying Terminal Conditions

For the previously disclosed measurements with large diameters, the experimental arrangement looked something like that shown in Fig. 12(a). Another experimental arrangement used for comparison purposes was that shown in Fig. 12(b). Here the inner conductor of the measuring line was the same diameter as the antenna. In fact, the antenna was simply the extension of the inner conductor. The system was so arranged that no insulators were in the measuring line between the point of measurement and the antenna. In these comparative measurements, the antenna diameter was maintained at 20.6 degrees. Three sizes of tubing were chosen for the outer conductor of the transmission line. The diameters of the transmission line as well as the characteristic impedance are given in the captions for Figs. 13 and 14.

Fig. 13 shows the measured resistance values for the arrangements, while Fig. 14 shows the corresponding reactance curves. Curve A in both figures shows the measured values for the arrangement of Fig. 12(a), with a diameter of 20.6 degrees. For this diameter, (6) shows that the shunt capacitive reactance is 65.0 ohms.

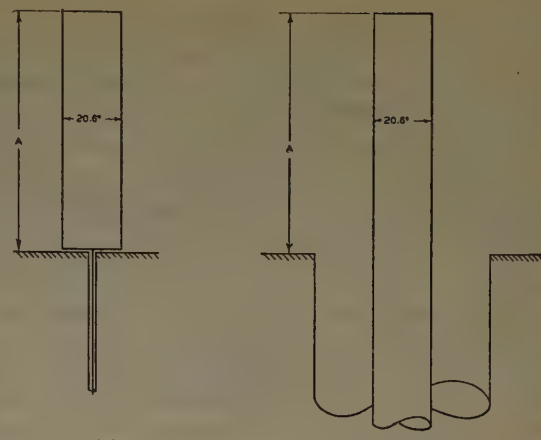


Fig. 12—Experimental arrangement for obtaining curves in Figs. 13 and 14. (a) For curve A. (b) For curves B, C, and D.

To knock out the effect of this shunting reactance, we may imagine an inductive reactance in shunt with the antenna, where this auxiliary reactance has a value of 65.0 ohms. Curve E on Figs. 13 and 14 was computed in exactly this fashion.

For instance, with an antenna length of 100 degrees, curve A shows that R_A is 42.0 ohms and X_A is -39.5 ohms. Then to find the impedance without the shunt capacitance, we calculate the parallel circuit conditions.

$$R_E + jX_E = \frac{j65.0(42.0 - j39.5)}{42.0 + j25.5} = 74.0 + j20.5 \text{ ohms.}$$

Examination of Figs. 13 and 14 shows that curve E fits in with the group formed by curves B, C, and D, particularly with regard to reactance values. This illustrates the point that the excessive base shunting reactance materially effects the measured impedance values. The difference between curves B, C, and D may be attributed again to changing terminal conditions.

The fact that curve E does not conform better to the curves B, C, and D is probably due to the fact that the simple conditions postulated in setting up (6) do not take full account of conditions near the terminals, and

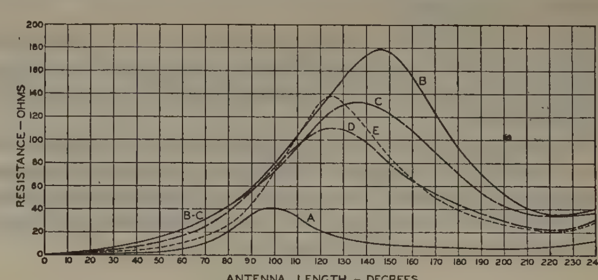


Fig. 13—Resistance as a function of antenna length A. The diameter D is 20.6 degrees.

Curve A—The arrangement shown in Fig. 12(a).
Curve B—The arrangement of Fig. 12(b), with the diameter of the outer conductor equal to 74 degrees. The characteristic impedance of the transmission line is 77.0 ohms.
Curve C—The outer conductor diameter is 49.5 degrees, and the transmission line has a characteristic impedance of 52.5 ohms.
Curve D—The diameter of the outer conductor is 33 degrees. The characteristic impedance is 28.3 ohms.
Curve E—This curve was obtained by tuning out the base reactance with an inductive reactance of 65.0 ohms.

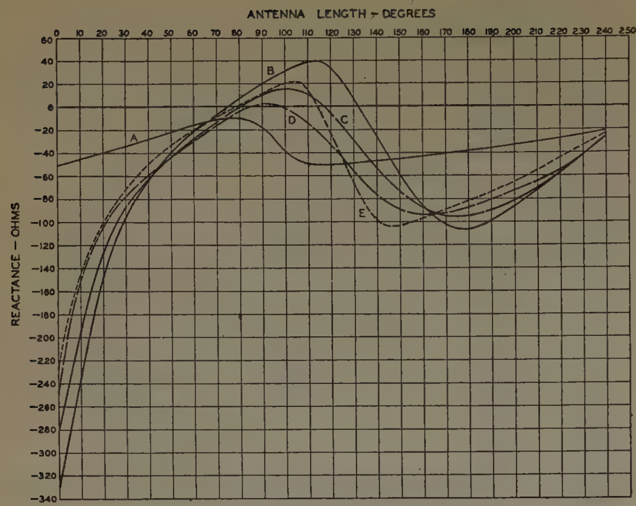


Fig. 14—Reactance curves corresponding to the resistance curves of Fig. 13.

in addition to the fact that curve A was measured at 60 megacycles, while curves B, C, and D were obtained at a frequency of 540 megacycles.

VII. Comparison of Impedance with Top of Radiator Closed and Open

Some workers in the field have suggested that results obtained with the radiator closed at the top would be different than when the radiator is open.[1] The writers continually checked this point throughout the course of the experiments. A great number of measurements were made with an open radiator, and then repeated with a disk soldered into place at the top of the radiator. Particularly careful observations were made with a radiator 20 degrees in diameter.

It was originally planned to display these experimental data. This plan was abandoned when it was discovered that opening or closing the top of the radiator made not the slightest difference in the measured impedance.

[1] L. Brillouin, "The antenna problem," *Quart. Appl. Math.*, vol. I, p. 214; October, 1943.

VIII. Application of the Measured Curves to Center-Fed Dipoles

All the data presented in this paper have applied to an antenna fed against ground. In case a center-fed dipole is to be considered, the antenna length A throughout this paper becomes the half length of the dipole, while all values of resistance and reactance shown in this paper must be doubled to give the proper values for a dipole. Due consideration must also be given the terminal conditions.

IX. Conclusion

Measured values of resistance and reactance of cylindrical antennas operated against ground have been displayed in a number of ways. It has been demonstrated that the exact conditions at the terminals are extremely important in determining the impedance conditions.

Electronic Alternating-Current Power Regulator*

L. B. CHERRY†, ASSOCIATE, I.R.E., AND R. F. WILD†, ASSOCIATE, I.R.E.

Summary—**The object of this paper is to describe an electronic alternating-current power regulator, which is instantaneous and independent of frequency.**

The theory and design considerations governing a conventional circuit using gaseous discharge tubes are presented. The effect of the extent of voltage-limiting by the gas tubes on the degree of regulation is discussed.

A bridge-type circuit is described and its theory developed. The effect of the degree of unbalance of the bridge circuit on the degree of regulation is discussed. The application of these circuits for regulation of low power, particularly the use in electronic apparatus, is treated and performance data on both circuits are given.

Introduction

For certain applications there is a need for alternating-current power regulators for low power. One particular application is the supply of constant heater power for vacuum tubes in direct-current amplifiers, in which varying heater power is one of the main causes of objectionable drift.

The devices used most for stabilizing low-wattage alternating-current power derived from commercial power lines either have a time lag before compensation takes effect, are dependent upon a constant power-line frequency, or are objectionable from the viewpoint of weight and cost.

Since gaseous discharge tubes have been used successfully for regulation of direct voltage, it has been suggested that the voltage-limiting characteristics of these tubes be utilized also for regulation of alternating-current power. The literature shows proposals to use gaseous discharge tubes connected across the primary winding of a power transformer.[1,2] Such an arrangement yields a degree of regulation which may satisfy certain

* Decimal classification: 621.375.1. Original manuscript received by the Institute, October 4, 1944; revised manuscript received, December 7, 1944.

† Brown Instrument Company, Philadelphia 44, Pennsylvania.

[1] G. F. Lampkin, "A simple A. C. voltage regulator," *Electronics*, vol. 10, pp. 30, 31, 36, 39, 40; August, 1937.

[2] M. H. Sweet, "A fluorescent lamp voltage stabilizer," *Electronics*, vol. 13, pp. 60–62; August, 1940.

requirements. A higher degree of constancy of alternating-current power, however, is attained by means of a new circuit which is essentially a bridge circuit employing gas-discharge tubes in one arm of the bridge. Both of these circuits yield instantaneous control of the alternating-current power, are independent of power-line frequency, and can be built at relatively low cost.

Equivalent Circuit for Gaseous Discharge Tubes

Before the theory of the control circuits to be described is discussed, the equivalent circuit of a gaseous discharge tube will be briefly analyzed. The equivalent circuit of such a tube is formed by a source of electromotive force E_0 in series relation with a resistor R_T.

In order to obtain the value E_0 of the electromotive force, the regulation characteristic, shown in Fig. 1,

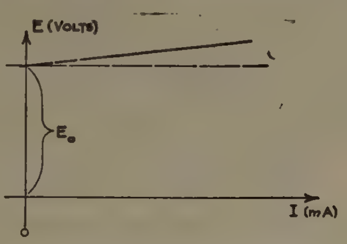


Fig. 1—Gas-tube characteristic.

is extended to the left until it intersects the voltage axis at the desired value E_0, for which the tube current is zero. The resistance value of resistor R_T is determined by the slope of the regulation characteristic. The characteristic shows that the voltage drop across the tube increases as the tube draws more current. Hence, an analogy can be made between the tube operation and the charging of a storage battery having an electromotive force E_0 and an internal resistance R_T, since the current through a battery on charge increases as the charging voltage is increased. Consequently, this equivalent circuit can be substituted for gas-discharge tubes in the circuit analysis. Obviously, in the case of alternating-current power regulation, the polarity of the electromotive force E_0 is reversed during alternate positive and negative half cycles of the alternating voltage.

Conventional Alternating-Current Power-Regulator Circuit

Fig. 2(a) shows a conventional alternating-current power-regulator circuit comprising a resistive load R_L parallel to which two gas-discharge tubes are connected in opposite polarity. The provision of two gas tubes, connected as shown, is believed advisable since most commercially available gas-regulator tubes are designed primarily for unidirectional operation. Connected in series relation with the combination of the gas tubes and load resistor, is a resistor R_1, provided for the purpose of limiting the maximum current through the gas tubes to its permissible value. The alternating-current power-line voltage applied to this circuit is assumed to be sinusoidal, as indicated.

Because of the sinusoidal variation of the applied line voltage, it is necessary to consider two conditions of the circuit, namely the condition in which the gas tubes are nonconducting and the condition in which they are conducting. These two circuit conditions are illustrated in Figs. 2(b) and 2(c). Fig. 2(d) shows the voltage drop

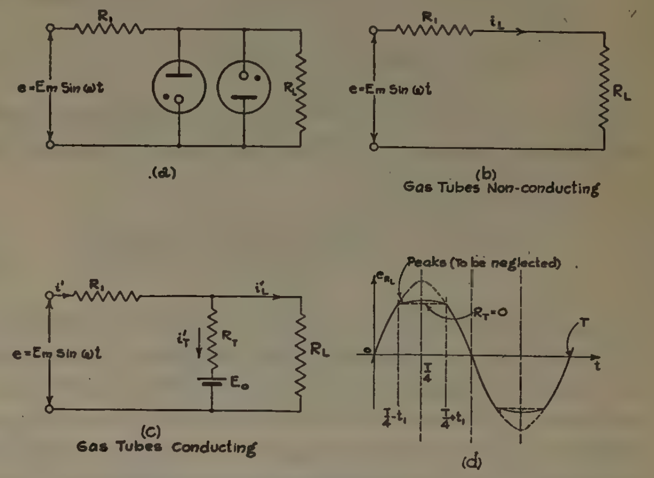


Fig. 2—Equivalent circuits of conventional-type regulator and resultant wave form.

across the load R_L which can be seen to deviate considerably from a sinusoidal wave shape. Since the circuit is to provide constant power, this is of little consequence as long as the effective value of this voltage, or of the corresponding load current, can be controlled to a relatively constant value.

In order to simplify the theoretical circuit analysis, the peaks appearing on the voltage curve, due to the difference between ignition and operating voltages of gas-discharge tubes, as well as the fact that the extinction voltage is lower than the normal operating voltage, will be neglected. It will also be assumed that ignition and extinction of the gas tubes occur at equal intervals before and after the peak values of the voltage applied to the tubes. The curve also shows that the voltage drop across the tubes does not remain perfectly constant during the interval of tube conduction. Finally, the internal impedance of the power source, which in the case of a commercial power line is very low, will also be neglected.

Equations (1), (2), (3), and (4) are derived by simple

$$i_L = \frac{e}{R_1 + R_L} \tag{1}$$

$$e - i'R_1 - i_T'R_T - E_0 = 0 \tag{2}$$

$$E_0 + i_T'R_T - i_L'R_L = 0 \tag{3}$$

$$i' = i_T' + i_L' \tag{4}$$

application of Kirchhoff's laws to the circuits shown in Figs. 2(b) and 2(c). The expression for the instantaneous load current for the condition of nonconducting gas tubes is given directly in (1), whereas the corresponding expression for the instantaneous load current for the

condition of conducting gas tubes is obtained by solving (2), (3), and (4) for $i_{L'}$. Equation (5) results.

$$i_L' = \frac{e + E_0(R_1/R_T)}{R_1 + R_L(1 + (R_1/R_T))} \tag{5}$$

from this solution. Equations (6) and (7) give expressions for the power supplied to the load during the inter-

$$P_1 = \frac{1}{(T/4) - t_1} R_L \int_0^{(T/4)-t_1} (i_L)^2 dt \tag{6}$$

$$P_2 = \frac{1}{t_1} R_L \int_{(T/4)-t_1}^{T/4} (i_L')^2 dt \tag{7}$$

vals in which the gas tubes are nonconducting and conducting respectively. The total power supplied to the load is given by (8).

$$P = \frac{R_L \int_0^{(T/4)-t_1} (i_L)^2 dt + R_L \int_{(T/4)-t_1}^{T/4} (i_L')^2 dt}{T/4}. \tag{8}$$

Inspection of (6), (7), and (8) in connection with Figs. 2(b) and 2(c) readily shows that the power varies with the duration of the interval of conduction, which is determined by the amplitude of the applied line voltage. While the power can be computed by means of (8), as shown later, this equation becomes too complex for a convenient qualitative indication of the degree of regulation.

It was found simpler to make a qualitative analysis in terms of effective load current, which must also approach a constant value for good power regulation. Equation (9) shows the current and voltage relationship in this circuit in the absence of gas tubes. In this equation

$$I_m = E_m/(R_1 + R_L) \tag{9}$$

E_m and I_m designate voltage and current amplitudes, respectively. In order to correlate the conditions of nonconduction and conduction of the gas tubes, it is necessary to assume that the load current immediately before and after ignition and extinction remain the same. No appreciable error is introduced by making this assumption. This particular value of load current may be termed the transitional load current and designated by i_{L_0}. Making this assumption, (10) can be written, since

$$i_{L_0} = E_0/R_L \tag{10}$$

the voltage drop across the load resistor equals E_0 at the instant immediately preceding ignition of the gas tube. Designating the effective value of load current by I', a relationship between I', i_{L_0} and I_m can be found, as set forth in (11), if it is assumed also that a perfect regulator

$$\frac{I'}{i_{L_0}} = \sqrt{2}\left[\frac{1}{\pi}\left[\frac{1}{2}\left(\frac{I_m}{i_{L_0}}\right)^2 - 1\right] \text{arc sin} \left(\frac{I_m}{i_{L_0}}\right)^{-1} - \frac{1}{2\pi}\left(\frac{I_m}{i_{L_0}}\right) \cos \text{arc sin} \left(\frac{I_m}{i_{L_0}}\right)^{-1} + \frac{1}{2}\right]^{1/2} \tag{11}$$

tube having no internal resistance is used. The transitional load current i_{L_0} in a given circuit depends solely upon the tube characteristics and the load resistor, and is therefore considered as constant. Hence, this equation shows the effective load current I' as a function of the ratio I_m/i_{L_0}, which again is indicative of the relative duration of the interval of gas-tube conduction. It readily can be seen from (11) that I' approaches the value i_{L_0} for increasing values of I_m/i_{L_0}. The ratio I_m/i_{L_0} is directly proportional to the amplitude E_m of the applied voltage, as set forth in (12). This means that

$$I_m/i_{L_0} = (E_m/E_0)(1/[1 + R_1/R_L]). \tag{12}$$

for an increasing amplitude E_m the wave shape of the load current approaches that of a square wave, for which the effective value equals the amplitude. For this ultimate hypothetical condition the effective load current would be totally independent of fluctuations of the amplitude of the applied line voltage.

Fig. 3 illustrates the relationship between the ratio I'/i_{L_0} and the ratio I_m/i_{L_0}, as set forth in (11).

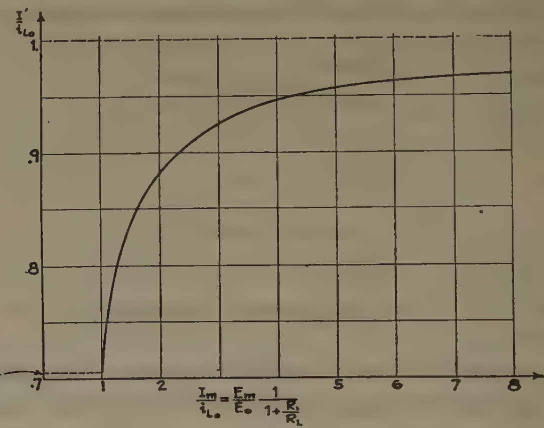


Fig. 3—Plot of (11) indicating the degree of regulation.

To obtain improved regulation, the ratio I_m/i_{L_0} can be increased by increasing the amplitude E_m of the applied line voltage, or by choosing a gas tube which ignites at a lower voltage and thereby effectively decreasing E_0. The values of the current-limiting resistor R_1 and E_m are interrelated, inasmuch as any substantial increase of R_1 necessitates an increase of E_m in order to ignite the gas tubes. Any increase of E_m, however, also improves the regulation, as mentioned before.

Table I gives experimental and calculated values of power for two different values of applied power line voltage, above and below 110 volts, for the circuit constants shown. Values are shown for the unregulated power as well as experimental and calculated values for

TABLE I

$R_1 = 155\Omega$; $R_L = 512\Omega$; VR-90 Tubes; $R_T = 53\Omega$ (approx.)

Line Voltage Volts (r-m-s)	Power (Watts) Unregulated	Regulated Experimental	Regulated Calculated Using Eq. (8)	Regulated Calculated Using Eq. (11)
106	12.95	12.46	10.55	9.66
115	15.43	13.45	11.5	10.07

Change in Line Voltage	Change in Power			
9	2.48	0.99	0.95	0.41

regulated power. It is seen that the values computed by using the more accurate power equation (8) are lower than the experimental values, due to the simplifying assumptions made in the derivation of this equation. The values computed by using (11) deviate still further from the experimental values, because of the additional assumption of perfectly regulating tubes. Table I shows that for a certain change in line voltage an improvement of approximately 2.5 to 1 is obtained experimentally by regulation. It also shows that the calculated values indicate better regulation than that actually obtained, because of the assumptions made.

The Bridge Circuit

Improved regulation is obtained by means of the bridge circuit shown in Fig. 4(a), comprising resistors R_1, R_2, R_3 and the gas-discharge tubes VR connected in

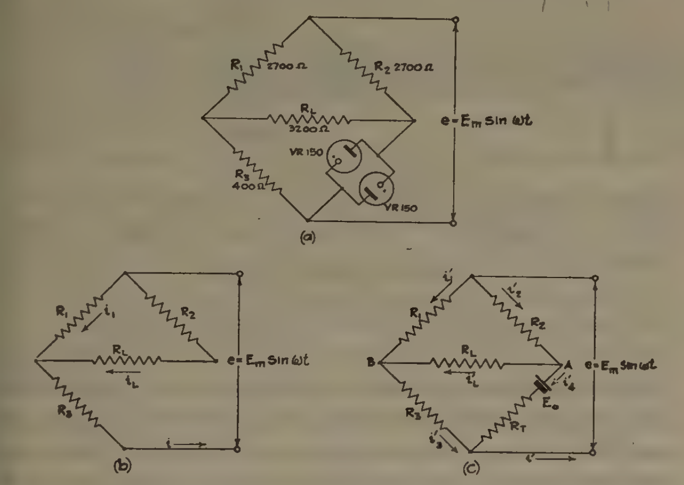


Fig. 4—Circuit of resistance bridge-type regulator together with equivalent circuits for nonconducting gas tube (b) and conducting gas tube (c).

the arms of the bridge, as shown. A resistive load R_L is connected in the diagonal of the bridge between the junction of resistors R_1 and R_3, and the junction of resistor R_2 and the gas-discharge tubes. Power-line voltage is applied across the other diagonal of the bridge, and is indicated to be of sinusoidal wave shape.

Again two different circuit conditions exist during the conducting and nonconducting intervals of the gas tubes, respectively, which are illustrated in Figs. 4(b) and 4(c). In Fig. 4(c), the gas tubes are replaced by their equivalent circuit.

If this bridge circuit is balanced, a degree of power regulation is obtained comparable to that of the conventional circuit just discussed.[3] Considerably better regulation is obtained if the bridge is unbalanced. The instantaneous load current can then be made to decrease for an increase in amplitude of the applied line voltage during intervals of tube conduction, so as to compensate for a corresponding increase in instantaneous load current during intervals of nonconduction. For this reason, the unbalanced bridge was further investigated.

Equations (13) to (15), and (17) to (22) are derived by application of Kirchhoff's laws to the circuits of Figs. 4(b) and 4(c). From these equations the instantaneous load-current equations (16) and (23), and the power equations (24) and (25) for nonconduction and conduction of the gas tubes respectively, are derived. An expression for total power is given in (26).

$$i = i_1 + i_L \tag{13}$$

$$e - i_L(R_2 + R_L) - iR_3 = 0 \tag{14}$$

$$i_1R_1 - i_L(R_2 + R_L) = 0 \tag{15}$$

$$i_L = \frac{e}{R_3 + (1 + R_3/R_1)(R_2 + R_L)} \tag{16}$$

$$e - i_1'R_1 - i_3'R_3 = 0 \tag{17}$$

$$E_0 - i_L'R_L - i_3'R_3 + i_4'R_T = 0 \tag{18}$$

$$-i_1'R_1 + i_L'R_L + i_2'R_2 = 0 \tag{19}$$

$$i_3' = i_1' + i_L' \tag{20}$$

$$i_2' = i_L' + i_4' \tag{21}$$

$$i' = i_3' + i_4' \tag{22}$$

$$i_L' = \frac{e\left(\frac{R_1}{R_2} - \frac{R_3}{R_T}\right) + E_0\left(\frac{R_1 + R_3}{R_T}\right)}{R_3\left(\frac{R_1}{R_2} - \frac{R_3}{R_T}\right) + (R_1 + R_3)\left[\frac{R_L + R_3}{R_T} + \frac{R_2 + R_L}{R_2}\right]} \tag{23}$$

$$P_1 = \frac{1}{(T/4) - t_1} R_L \int_0^{(T/4)-t_1} (i_L)^2 dt \tag{24}$$

$$P_2 = \frac{1}{t_1} R_L \int_{(T/4)-t_1}^{T/4} (i_L')^2 dt \tag{25}$$

$$P = \frac{R_L\int_0^{(T/4)-t_1}(i_L)^2 dt + R_L\int_{(T/4)-t_1}^{T/4}(i_L')^2 dt}{T/4}. \tag{26}$$

Inspection of (23) shows that the multiplying factor of the instantaneous applied voltage e can be made negative by properly unbalancing the bridge circuit. Since e is the only variable in this equation the instantaneous load current can then be made to decrease with increasing magnitude of e. Preferably the bridge constants and tubes are so chosen that the second term of the numerator is substantially greater than the first term, so that the amount of decrease of the load current i_L' during tube conduction is just sufficient to compensate for a corresponding increase of the load current i_L over its normal value during nonconduction, caused by a fluctuation of the applied line voltage e. The greater the second term of (23), the greater will be the load current and the power transmitted to the load.

Fig. 5 shows two oscillograms illustrating the decrease in instantaneous load current during gas-tube conduction for increasing amplitude of line voltage, specifically for line voltage values of 175 and 250 volts (root-mean-square).

The phenomenon illustrated by Fig. 5 causes the effective load current to increase slightly to a maximum value and then to decrease again, when the line-voltage amplitude is continuously increased through a

[3] T. R. Harrison, United States Patent No. 2,211,114.

predetermined operating range. This can be explained qualitatively by the fact that the gas tubes conduct over a greater part of the cycle for increasing amplitudes of line voltage, so that the decrease in instantaneous load current during the tube-conduction interval overcompensates for the increase in instantaneous load current during the nonconduction interval. By adjusting the values of resistors R_1, R_2, and R_3, the value

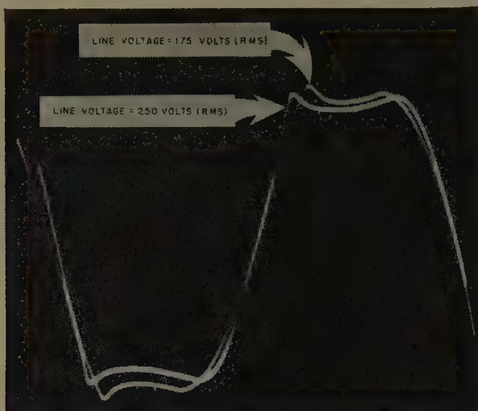


Fig. 5—Wave form of output current of bridge-circuit regulator.

of line-voltage amplitude at which the change of effective load current changes from an increase to a decrease can be varied to suit the operating range. The effect just described is instrumental in rendering better regulation than could be obtained with a balanced bridge, in which the effective load current increases constantly with increasing line-voltage amplitude.

In the design of the unbalanced bridge the factor $[(R_1/R_2)-(R_3/R_T)]$ of the instantaneous line voltage e in (23) for the instantaneous load current i_L' should be in the order of -10 to -20. R_T was found to be approximately 35 ohms for a VR 150 tube; however, this value varies from tube to tube. The value of resistor R_2 is chosen from the viewpoint of limiting the gas tube current, and should be about 2000 or 3000 ohms.

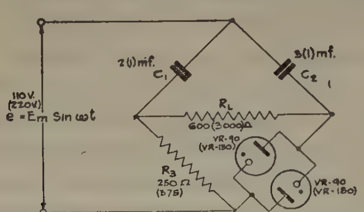


Fig. 6—Circuit of the resistance-capacitance bridge regulator.

Fig. 4(a) shows typical values, which are not critical, for a circuit operating from an applied voltage of 275 to 385 volts (root-mean-square). In this case, a 40 per cent change in applied voltage produces a change in effective load current of about 1 per cent of a nominal current of 27 milliamperes. For this case the efficiency of the circuit is between 4 and 8 per cent, depending upon the applied voltage. This poor efficiency is largely due to power dissipation in the resistors R_1 and R_2.

In order to improve circuit efficiency a new bridge circuit, shown in Fig. 6, was investigated, in which the resistors R_1 and R_2 are replaced by capacitors C_1 and C_2. The theory and principle of operation are the same as those developed for the resistance bridge.

Applications

For an example of an application of the bridge-circuit power regulator the heater of a type 6P5 vacuum tube and a suitable heater transformer were chosen as the load. Fig. 6 shows circuit constants for typical circuits for operation on 110-volt and 220-volt power lines, respectively. For measurement of the effective load current, the load, comprising the heater and heater transformer, was replaced by an equivalent purely resistive load.

TABLE II

C_1 in microfarads	C_2 in microfarads	R_3 in ohms	R_L in ohms	Voltage-Regulator Tubes Used	Load current in milliamperes and per cent change in load current	Per cent change in 5-milliamperes plate current of 6P5 tube	Per cent change in 5-milliamperes plate current of 6P5 without use of regulator
Line Voltage = 110 ± 10 per cent							
2	3	250 approx.	600	VR-90	73 ± 0.35 per cent	±0.01 per cent	±4 per cent
Line Voltage = 220 ± 10 per cent							
1	1	375 approx.	3000	VR-150	32 ± 0.35 per cent	±0.01 per cent	—

Table II gives the circuit constants and operational data for the circuit shown in Fig. 6. For both 110-volt and 220-volt operation the change in effective load current was ±0.35 per cent for a change in line voltage of ±10 per cent of the nominal line voltage, the nominal effective load currents being 73 milliamperes and 32

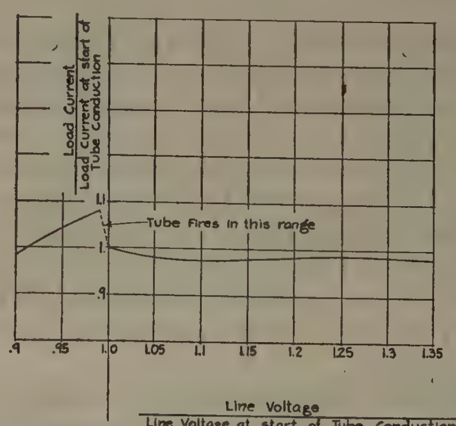


Fig. 7—Experimental curve indicating the degree of regulation given by the resistance-capacitance bridge.

milliamperes, respectively. Without regulation the change in effective load current would have been 10 per cent instead of 0.35 per cent, so that the change in effective load current is about 1/28 of what it would have been without regulation. Finally, the effect of regulation upon the plate current of a 6P5-type vacuum tube was

measured, in order to demonstrate the usefulness of the regulator in connection with direct-current amplifiers. Without regulation a plate-current change of ± 4 per cent about a nominal value of 5 milliamperes is produced by a line-voltage change of ± 10 per cent of the nominal line voltage of 110 volts. However, with the unbalanced-bridge-regulator circuit the plate-current change is reduced from 4 to 0.01 per cent, or one four-hundredth of its original value. Such a reduction in plate-current fluctuation obviously should contribute substantially to a more stable direct-current amplifier.

A typical experimental curve showing the degree of regulation obtainable by the use of the resistance-capacitance bridge is given in Fig. 7. The slight downward tendency of the curve for the highest line voltages is explained earlier in the discussion of Fig. 5. The efficiency of the resistance-capacitance bridge regulator varies from 30 to 50 per cent depending upon the line-voltage amplitude.

Since the values of capacitance used in this bridge are not critical, this bridge is substantially independent of power-line frequency, as initially claimed, operates without time lag, and is capable of handling any power which the current capacitance of the gas-discharge tubes will permit.

Obviously, the use of this power regulator is not restricted to the specific application discussed above, but may be extended to any other application in which close control of low values of alternating-current power is required.

Discussion on

"Design of Electronic Heaters for Induction Heating"*

J. P. Jordan

George H. Brown:[1] In his paper on electronic heaters, Mr. Jordan states that the rate of heat input is proportional to the square root of the frequency. It is true that his equations (1) and (3) do indicate this point. However, this is on the assumption that his quantity H_t, the tangential component of magnetic flux at the surface of the charge, is independent of frequency. This in turn implies that the current in the exciting coil is independent of frequency. This is, of course, true where the inefficient practice of placing the work coil in series with the tank-circuit inductance is used. However, the writer has found that transformer coupling to the tank circuit pays real dividends in obtaining maximum power from a given vacuum-tube complement. Then at low frequencies, high currents flow in the work coil. Thus the factor H_t for a constant power input varies inversely as the one-fourth power of the frequency.[2] If this factor is inserted in Mr. Jordan's equation (1), the power dissipated by eddy currents ΔP is seen to be independent of frequency. This effect has been further amplified by the writer in a recent paper which shows that the efficiency of operation is practically constant over a wide range of frequencies.[2]

A suitable coupling transformer which is useful in many induction-heating applications is shown in Fig. 17 of the writer's paper just referred to. The use of this transformer serves to vitiate another conclusion drawn by Mr. Jordan. He states that a Hartley oscillator is ruled out of the induction-heating picture, because the grid-phase relationship is altered adversely by coupling to the load. However, when the proper transformer is used, with the primary coil grounded at the proper point so that one end of the primary serves as the grid coil and the other end serves as the plate coil, the effect of loading is to shift both the plate and grid voltages in the same direction, thus preserving the desired 180-degree phase relation. In our laboratory, we use the Hartley circuit in preference to a Colpitts. The Hartley circuit requires a single fixed condenser, while the Colpitts requires a split capacitor, both sides of which must be altered when it is desired to change the grid excitation. This change in grid excitation is quite easily obtained in the Hartley circuit by moving the ground tap on the primary of the transformer. In addition, it has been our observation that we secure greater stability with changing load when using a Hartley circuit which is transformer coupled to the work coil, with at least as good an efficiency as we have secured with a Colpitts circuit.

* Proc. I.R.E., vol. 32, pp. 449–452; August, 1944.

[1] RCA Laboratories, Princeton, New Jersey.

[2] George H. Brown, "The efficiency of induction heating coils," *Electronics*, vol. 17, pp. 124–129; August, 1944.

J. P. Jordan:[3] The discussion submitted by Dr. Brown deals with a phase of the subject which was intentionally omitted from the original article. The paper was intended as a discussion of the factors entering into the design of a flexible, general-purpose oscillator, which could be easily applied to a wide range of jobs by any technician. To achieve this end, it has been the writer's experience that the use of multiturn coils connected directly in the tank circuit will cover the majority of all applications with the least difficulty in coil design. Multiturn coils are easy to wind, permit ready adjustment of loading, and are more efficient than any other method of application. Of course, there are jobs requiring the use of single-turn, high-current coils where an output transformer or a shunt capacitor is indicated.

[3] General Electric Company, Schenectady 5, New York.

But, for general-purpose industrial machines, it is far better to design the oscillator for use with multiturn coils in series with the tank, and then adapt the output transformer to the oscillator when an application arises which requires it.

The output transformer has its greatest application under three conditions—first, when it is necessary to use very high rates of power input per unit area; second, when the physical shape of the part necessitates the use of single-turn, high-current coils; and third, when working conditions require the use of the minimum possible operating voltage. Such cases arise when hardening by the self-quenching method, thin surface hardening of restricted areas, and the hardening of grooves or heating of such parts as tees, etc., when a two-piece coil is necessary. However, since the mutual inductance of the usual air-core transformer is relatively low, it cannot be used efficiently over a wide range of coil inductances, thus necessitating a variety of sizes and turn ratios to cover jobs of different sizes. This factor, together with those mentioned above, restricts the application of any oscillator which can be used only with output transformers.

Dr. Brown has pointed out that for all practical purposes the efficiency of operation remains constant over a wide range of frequencies, while high currents are more easily obtained with output transformers at the lower frequencies. However, since the oscillator under discussion was primarily designed for use with multiturn coils, other factors influenced the choice of frequency.

The Hartley circuit which Dr. Brown recommends is an excellent one for some laboratory uses. The writer has used several such oscillators in the past for special applications, and has found them economical to construct, stable, and amenable to ready alteration for laboratory developmental use. However, for the reasons given previously, the Colpitts or coupled-grid circuits appear to the writer to be preferable for an industrial electronic heater which is to be used both with and without output transformers.

George H. Brown:[1] Mr. Jordan's reply to my discussion of his paper indicates that he has drawn a different conclusion from his experience than I have from mine. I am of the opinion that the use of an output transformer takes care of the majority of the applications with the least difficulty.

Institute News and Radio Notes

Board of Directors

February 7 Meeting: At the regular meeting of the Board of Directors, which was held on February 7, 1945, the following were present: W. L. Everitt, president; G. W. Bailey, executive secretary; S. L. Bailey, W. L. Barrow, E. F. Carter, Alfred N. Goldsmith, editor; R. F. Guy, R. A. Heising, treasurer; Keith Henney, Haraden Pratt, secretary; B. E. Shackelford, D. B. Sinclair, W. O. Swinyard, H. M. Turner, H. A. Wheeler, W. C. White, and W. B. Cowilich, assistant secretary.

Executive Committee Actions: The actions of the Executive Committee, taken at its January 9, 1945, meeting, were ratified.

Constitutional Amendments: Consideration was given to amending the Constitution in a manner to provide for district directors, and for the appointment of a special committee to study the situation involving geographical representation, the possible reduction of Board meetings to four a year, and the desirability of increasing the number of members on and duties of the Executive Committee.

The following motion was passed:

"It was moved to appoint a committee to study the management of the Institute by the Board to the end of proposing modifications in methods that will relieve the Board of unnecessary details, having in mind reducing the number of Board meetings and moving toward regional representation."

H. A. Wheeler, chairman; G. W. Bailey, W. L. Barrow, R. A. Heising, Haraden Pratt, and W. O. Swinyard were appointed to the committee mentioned.

President's Visits: President Everitt stated that he plans to visit Institute Sections in Texas and the Middle West and on the Pacific Coast during February and March.

Standing Committees: The appointment of the Committee personnel, which is to be found on page 275 of this issue, was unanimously approved.

Building-Fund Committee: Dr. Shackelford, chairman, reviewed matters relating to the building-fund campaign, and the following actions resulted from the discussion:

Canadian Contributions: Reference was made to the February 3, 1945, letter from Honorable J. L. Ilsley, Canadian Minister of Finance, which was addressed to Mr. Hackbusch of the I.R.E. Canadian Council. This letter indicates the regulations on sending funds to organizations outside Canada.

Following consideration, this motion was unanimously approved:

"It was moved that the Board recommends that the Building-Fund Committee take whatever action is considered suitable to facilitate the obtaining of funds to be contributed in Canada, providing that such funds are transferable after the end of the war without substantial tax liability at the time."

Initial Gifts: A number of substantial donations have already been received.

Honorary Chairman and Vice-Chairman: Powel Crosley, Jr., and L. P. Wheeler have been chosen for the honorary chairmanship and vice-chairmanship, respectively, of the Building Fund; and it was noted with appreciation that they have accepted the corresponding posts.

Education Committee: Unanimous approval was given to the recommendation of the Education Committee that the Institute Sections form educational committees for the purpose of co-operating with the local educational institutions in furthering student guidance, arranging technical courses of study needed by industry, and assisting students and returning war veterans in obtaining jobs.

War Manpower Commission: Secretary Pratt distributed copies of a letter, covering his reappointment as Consultant in the Office of the Chairman, War Manpower Commission, effective January 9, 1945.

B. J. Thompson Memorial: Secretary Pratt, as chairman of the special committee on a memorial for the late Mr. Thompson, reported on the proposal that the income from a fund, to consist of contributions from a group of his close friends and associates (which includes RCA employees and others) be given as a recurrent prize for an outstanding paper, by a young author, recently published by the Institute, and that such fund be administered by the Institute.

Following the discussion, it was moved that the Board would gladly agree to the handling by the Institute of the stated fund,

which would also be administered by the Institute as an annual prize to such an engineer (under 30 years of age) submitting an outstanding paper published by the Institute.

The Institution of Electrical Engineers: Editor Goldsmith explained that in the December 13, 1944, letter from Secretary W. K. Brasher of the Institution of Electrical Engineers, his organization has offered IRE members the privilege of subscribing for its named publications at the listed prices, which are half of the normal annual rates:

"*JOURNAL*

"Part I (General)	10s.6d. ($2)
"Part II (Power Engineering)	15s.9d. ($3)
"Part III (Radio and Communication Engineering)	10s.6d. ($2)

"or

"all three Parts together . . 31s.6d. ($6) per annum.

"*SCIENCE ABSTRACTS*

"Section A (Physics Abstracts)	17s.6d. ($3.50)
"Section B (Electrical Engineering Abstracts)	17s.6d. ($3.50)

"or

"both Sections together . . . . 30s.0d. ($6)"

It was pointed out that a similar reduction (one half) on the Proceedings, in case of the IEE members, would result in the special rate of $6.00 a year ($10.00 less 50 per cent discount, plus $1.00 foreign postage), or the equivalent of annual dues for the Associate grade.

The motion to accept the special-price offer on the IEE publications for the IRE members, to be effective January 1, 1946, and subject to paper limitations, was unanimously approved.

Executive Committee

February 6 Meeting: The Executive Committee meeting, held on February 6, 1945, was attended by W. L. Everitt, president; G. W. Bailey, executive secretary; S. L. Bailey, W. L. Barrow, E. F. Carter, Alfred N. Goldsmith, editor; R. A. Heising, treasurer; Haraden Pratt, secretary; and W. B. Cowilich, assistant secretary.

Membership: The following transfers and applications for membership were unanimously approved: for transfer to Senior Member grade, J. F. Bates, Rinaldo DeCola, D. W. Gellerup, R. A. Henderson, F. P. Herrnfeld, C. B. Jones, A. W. Melloh, Earl Schoenfeld, W. M. Smith, E. K. Stodola, and D. P. Tiedemann; for admission to Senior Member grade, H. G. Booker, W. E. Bradley, Gregory Breit, W. C. Hahn, R. E. Samuelson, N. H. Searby, and Joseph Slepian; for transfer to Member grade, A. E. Anderson, E. F. Brooke, W. R. Clark, N. B. Coil, J. W. Davis, T. A. Elliott, R. C. Fancy, E. M. Guyer, F. W. Herrmann, W. E. Hudson, W. S. Klein, G. S. Ley, M. A. McLennan, R. J. Nunner, W. H. Ottemiller, Jr., T. B. Perkins, J. M. Pettit, L. D. Prehn, E. O. Ross, F. F. Seifert, H. S. Sheppard, H. L. Spencer, F. G. Suffield, J. E. Tapp, R. A. Whiteman, and C. R. Wischmeyer; for admission to Member grade, G. E. Bowler, P. B. Burley, L. C. Cahan, U. C. S. Dilks, S. B. Dunham, H. C. Florance, K. J. Gardner, B. K. Hawes, Jr., W. P. Jacob, C. E. McClellan, J. T. McNaney, C. H. Millar, A. W. Moody, D. S. Radmacher, E. H. Ross, H. G. Schick, Arnold Shostak, Henry Sturtevant, Frank Virgadamo, H. H. Warrick, L. L. Winter, and H. B. Yarbrough; Associate grade, 192; and Student grade, 81.

1945 Winter Technical Meeting: The Assistant Secretary stated that the registration totaled 3022 (including 1202 registered in advance and 50 women) and that 1180 attended the banquet, 558 the President's Luncheon, and 274 the Luncheon for men in the Armed Services. 395 membership applications were distributed during the four-day meeting, which terminated on January 27, 1945.

1945 Summer Convention: The 1945 Summer Convention scheduled to be held in Montreal during June will be canceled.

"Messrs. A, B, and C." The following Executive Committee appointments were made, and the duties assigned in each case are explained below:

"Mr. A." W. L. Barrow shall be in charge of Standardization and other Technical Committees.

"Mr. B." S. L. Bailey shall be in charge of Advertising, Conventions and Conferences, and Sections.

"Mr. C." E. F. Carter shall be in charge of Admissions, Membership, and Public Relations Committees.

YEARBOOK: It was moved and unanimously approved to send a copy of the Yearbook automatically, without charge, to each member (except in the case of Student members) and to subscribers. The YEARBOOK will be made available to anyone for purchase in limited quantities at $5.00 a copy.

It was decided to insert suitable brief biographies of all Fellows in the forthcoming YEARBOOK and, at the September meeting of the Executive Committee, to consider extending the biographical data to the members of the Senior-Member grade beginning with a later YEARBOOK following the edition now in preparation.

It was unanimously recommended to the Board that the records for the YEARBOOK be changed to show the year of election to Member grade prior to the adoption of the constitutional amendment creating the grade of Senior Member, as the year of election to the grade of Senior Member in all such cases.

Manual of Procedure for Technical Sessions: President Everitt submitted a proposed draft of the manual, "The Presentation of Technical Developments before Professional Societies," which he had prepared.

It was decided to publish this material in the PROCEEDINGS and to provide 5000 reprints for use by Sections and at national meetings of the Institute.

1945 Winter Technical Meeting

With a total registration of slightly more than 3000, the 1945 Winter Technical Meeting of the Institute, held at the Hotel Commodore, New York, January 24 to 27 inclusive, set a new high mark in attendance and created a commendable record for sustained interest. Despite the wartime difficulties of train travel and a serious shortage of hotel accommodations, engineers from all parts of the country registered for the four-day Meeting. By laying out parallel sessions on a strict schedule and adhering to it, the Papers Committee was able to present 43 papers and one special session. The latter, a symposium on Wave Propagation, occupied the entire afternoon of the final day and produced the high spot of the WTM.

A full house was attracted to the joint session of the IRE and AIEE on the opening night to witness the award of the Edison Medal to Dr. E. F. W. Alexanderson and listen to addresses by the recipient and by Captain J. B. Dow, United States Navy, who discussed the Navy's electronic program. This event, the only one held outside the Hotel Commodore, took place in the auditorium of the Engineering Societies Building.

The annual banquet on Thursday night was attended by over 1200 members and guests. Extra tables were placed in every available space to accommodate the overflow. Prior to the principal address by Francis Colt de Wolf, chief, the telecommunications division, Department of State, Dr. W. L. Everitt, newly elected president of the Institute, awarded the Medal of Honor to Dr. H. H. Beverage; the Morris Liebmann Memorial Prize to Dr. W. W. Hansen; and twelve Fellowships to distinguished engineers in the radio and communications fields. Professor H. M. Turner, retiring president, also spoke.

Colonel V. B. Bagnall, U. S. Army, was the principal speaker at the luncheon on Friday honoring Dr. Everitt as the incoming president. Later in the day, at the conclusion of the afternoon technical session, visiting engineers were guests at a cocktail party made possible through the generosity of nearly forty manufacturers. Here again there was an attendance that far exceeded the estimates of the Arrangements Committee.

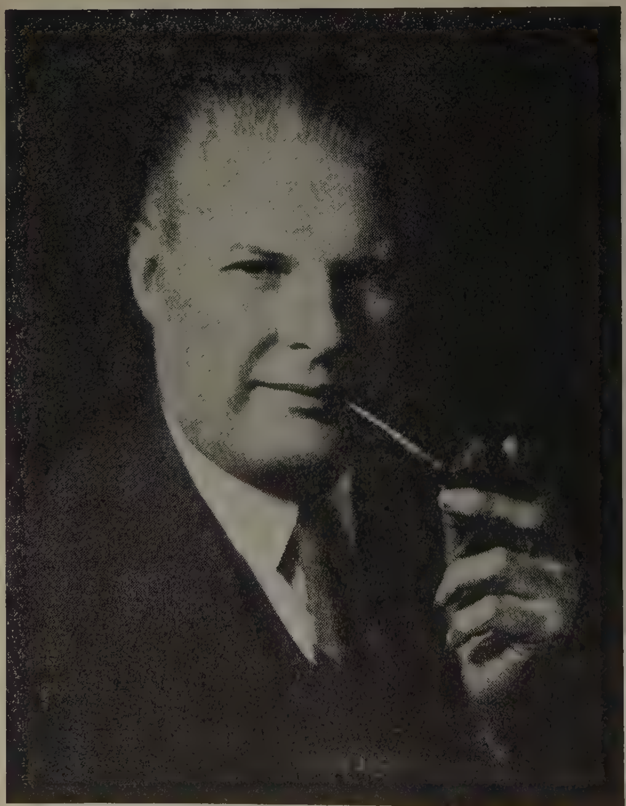
The luncheon on Saturday, which was held to honor servicemen, especially those from the Signal Corps stationed at Fort Monmouth, had been expected to close the 1945 WTM but a paper on "Wave Propagation" read on Thursday by K. A. Norton and E. W. Allen, Jr., had started a controversy which increased in interest and intensity during the remainder of the sessions. Recognizing the great importance of the subject, in view of the Federal Communications Commission's preliminary report on allocations, Dr. Everitt and the several committees concerned decided to hold a post-meeting session on Saturday afternoon.

(*Continued on page 274*)

1945 WINTE

Mr. Francis Colt de Wolf, Chief, Telecommunication Division, Department of State, Guest Speaker at Banquet. Professor Turner in Background.

Dr. William W. Hansen Receives Morris Liebmann Me Prize for 1944 from Dr. William L. Everitt. Lower left de Wolf.



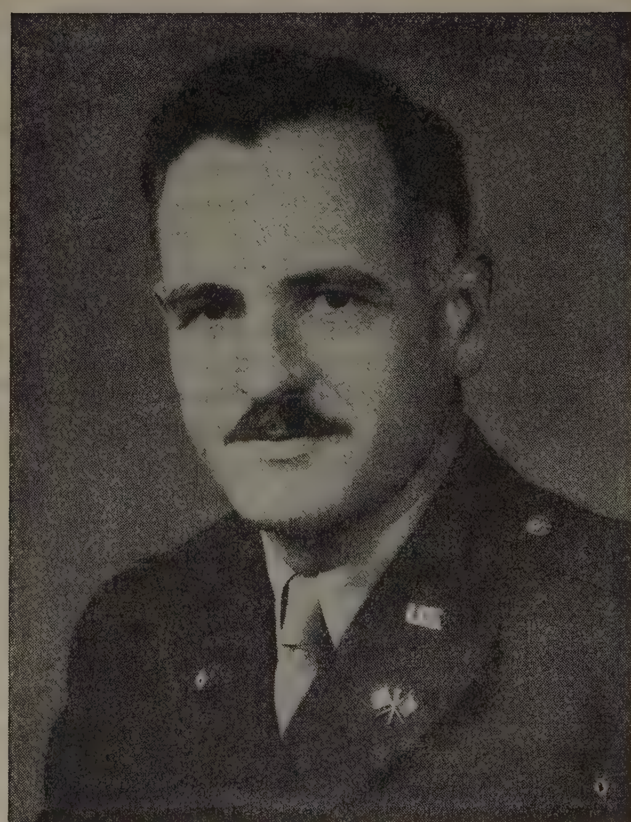
Dr. Harold H. Beverage, Recipient, Medal of Honor, 1945.

Dr. Everitt Presents Certificate of Fellowship to Dr. Orest Caldwell, who Made the Speech of Acceptance for a cipients of The Fellow Grade.

ECHNICAL MEETING

Captain Jennings B. Dow, United States Navy, Addresses the Joint I.R.E.-A.I.E.E. Meeting.

ENERAL COMMITTEE; 1945 WINTER TECHNICAL MEETING
ont row: M. B. Long; Frank Gunther; J. E. Shepherd, vice-nan; Austin Bailey, chairman; Helen M. Stote; Howard S. r, and Martin A. Gilman.
ck row: E. L. Bragdon, Carl E. Scholz, E. W. Herold, G. B. ey, W. B. Lodge, and E. J. Content.



Colonel V. B. Bagnall, United States Army, Guest Speaker at President's Luncheon.

Mr. H. B. Richmond, Banquet Toastmaster, and Dr. Everitt.

I.R.E. Building Fund

Francis Bacon, in "Maxims of the Law," says "I hold every man a debtor to his profession; from the which as men of course do seek to receive countenance and profit, so ought they of duty to endeavor themselves by way of amends to be a help and ornament thereunto."—John Howard Dellinger, National Bureau of Standards.

An Open Letter to the Chairman of the I.R.E. Building Fund

I DO NOT think the Building Fund can be divorced from the whole problem of the future of the Institute, and, therefore, items such as new services which are proposed must be integrated into it, because it all contributes to the broad, over-all plan.

Our society has developed in recent years at an unprecedented rate, both numerically and geographically. We have an opportunity, if we can present a united front, to take the leading part in the development of new services to the members, the profession, the industry, and the commonwealth. To do this we need (1) An aggressive, forward-looking program and (2) A unity of purpose, while at the same time, utilizing the contributions of all the members in determining policy.

To achieve these purposes, we must progress away from the present situation, where the voluntary services of the officers have been depended upon, not only to formulate policies, but also to administer the details of office procedure. During the war and for some time previous, we have been coasting along with an inadequate permanent staff, with the result that communications from and with the members have been neglected and other services have been meager or postponed to the future.

It is my firm conviction that in the development of a unified, aggressive organization, there is nothing more important than a well-trained permanent office staff under capable leadership having a high esprit de corps and an intense loyalty to the organization for which they are working. When this is developed, correspondence between headquarters and the Sections will be prompt and meaningful, the wishes of the Sections can be interpreted into Board matters, and a frequent rotation of officers and Directors, who no longer have to dabble with office detail, is possible and necessary to provide a refreshing flow of new blood between the Institute membership and its management.

To achieve these desired results, the three essential prerequisites are a capable full-time leader at headquarters, an adequate staff, and quarters conducive to work of a high caliber.

We have now secured the leadership by appointing Mr. George Bailey as our Executive Secretary. I have heard nothing but good comments upon this choice. He was chosen, among other things, because of his outstanding ability in office management, and his proved capability of organization leadership. We are also moving rapidly to secure a Technical Secretary and a Technical Editor, so that the officers will not be depended upon for the details of management. Thus, we shall have an adequate full-time staff, to co-ordinate our technical committees and editorial functions.

I quite concur with the Building Fund Committee that the need of the proposed new building by the Institute is urgent . . . —Lee de Forest.

The actual decision to embark upon the building-quarters campaign was a result of really hard work for the past two years. Anyone who steps into the crowded Institute headquarters can see that something had to be done and done soon. As a first step, an Office-Quarters Committee was appointed to secure additional space. They started out to look for space to rent and found that it was very scarce, arrangements for future growth were almost impossible, and proposed rentals were extremely high. The Board, after much discussion, then instructed the Quarters Committee to look into the possibility of purchase, not knowing whether we should put the limited Institute capital into down payment on a home which would have to be heavily mortgaged. Many locations were studied and the following condition was found to exist:

1. Any property which is suitably located, comes on the market for a short time and then disappears. Frequently, before we could examine a building, it would be off the market.
2. Prices were constantly going up.
3. The only possible way to purchase a home would be to have the cash on hand and move quickly, when the opportunity arose.

I am very happy to endorse your statement of the needs of the I.R.E. for a new building and endowment and to express my confidence in the Directors and the plan of the Building-Fund Committee.—G. W. Pierce.

The Board discussed thoroughly the matter of financing. Three plans (including some variations) were considered.

1. Part payment with present Institute funds and a mortgage on the balance.
2. A Building-Fund Campaign among the members only, where we might hope to get enough cash to buy the building and then gradually fix it up. This would saddle the Institute with a permanent increase in its fixed charges.
3. A campaign of the proportion now under way which would buy the building, fix it up in an appropriate fashion, and provide sufficient endowment to cover the increase in cost of operation above our present rental.

The Board was inclined in turn to each of these proposals but progressed to the certainty that the latter was the only proper course. By the time the thorough study had been made, it became evident that real-estate prices were going up, and that if we struck "while the iron was hot" we should be able to take advantage of the present favorable tax situation (that is, favorable for the campaign). Accordingly, it was decided to go ahead. I shall not repeat here all the arguments for the plan which have been given in the literature.

With reference to your letter of January 30th, I have no objection to using my name as a sponsor for the Building Fund of The Institute of Radio Engineers. It is a pleasure to assist the Institute as the Signal Corps of the Army has long been in close association with it.—Major General H. C. Ingles.

The Board discussed rather thoroughly the question of the completeness of the proposal which should be submitted in the Building Fund program. There is no vacant land available in a desirable location in New York for a new building, nor is it presently economical to purchase an existing building and demolish it in order to build a new one.

For these reasons, it seemed essential that the Institute have the cash on hand before it would dare buy a building to fit its present needs. It would be impossible to secure an option of sufficient length on a proposed building if the money must be collected later, because all real-estate owners will consider only short-time proposals for options and by the time the money could be collected, a desirable building would be sold.

I feel that it is extremely important for the future of the Institute that we try to get as much utility throughout the organization as possible, while at the same time, moving forward progressively.

W. L. Everitt, *President*
The Institute of Radio Engineers

War-Loan Bonds

Building-Fund subscribers can receive local war-loan credit by remitting to the Institute war bonds instead of cash or checks, thus discharging a patriotic duty at the same time that they are supporting the Institute's objectives. Series F bonds may be purchased at cost price of $18.50 upwards, or Series G from $100 upwards. It is very important that the bond be registered in the name: "The Institute of Radio Engineers, Incorporated," and not in the form in which checks will ordinarily be drawn, to: "I.R.E. Building Fund."

We are just entering the electronic era, and I would like to see the Institute in a position to carry on its functions fully in order to keep the United States in the lead in this field. I believe that one of the functions of the Institute should be that of serving as a liaison between the electronics industry and the Armed Services in order that our country will be better prepared to meet any emergency which may arise.—Joseph R. Redman, Rear Admiral, United States Navy.

For example, a subscriber who had committed himself to a payment of $25 quarterly might make one or more of his quarterly payments in the form of a check for $6.50 and a $25 Series F bond costing him $18.50. The Institute can make the necessary conversions from Series F to Series G and vice versa so that it may hold a total of $100,000 of these bonds. Note that Series E bonds, usually sold during drives to individual subscribers for $18.75 upwards, are not available both on account of limitation on holdings and limitation of registration to individuals.

Canadian subscribers will have their attention drawn to corresponding features in Canada by Mr. R. A. Hackbusch, of the Canadian Council.

The contributions made by the members of the I.R.E. have proved to be the most valuable and revolutionary for civilization, without exception. In a little more than a generation the combined contributions of radio physicists and engineers have become the world's most powerful influence, and the Institute should carefully guard and guide this giant.

In setting up your plans for a permanent home, you might bear in mind space for preserving and showing original developments and contributions to the art,—a small historic museum.—William Dubilier.

(Continued from page 269)

Among those who addressed a packed West Ballroom that day, in addition to Messrs. Norton and Allen, were Major E. H. Armstrong, C. M. Jansky, Jr., John D. Reid, Dale Pollack, and Allen B. DuMont. Sensing the impact of the arguments on many allied phases of radio, newspaper editors assigned reporters to cover the session and as a result, the Institute received wide recognition in the press.

One of the principal points of attraction throughout the WTM were the exhibits of manufacturers where many war-born products were available for inspection. Thirty-nine firms were represented with displays. This feature of the Winter Technical Meeting drew so many favorable comments that additional space for exhibits undoubtedly will be provided at future conventions.

Among the special plans made to entertain the wives of visiting members was a sightseeing trip to the Old Merchants House. Luncheons were held at Wanamakers and The Women Services Club; a special make-up demonstration was given at the Coty Salon, and a fashion show presented at the New York Dress Institute. Fifty women guests participated in these activities.

Music for the annual banquet was supplied by an orchestra donated by the Blue Network. Artists from the National Broadcasting Company entertained the servicemen at the luncheon given them on Saturday.

The General Committee for the 1945 Meeting, headed by Dr. Austin Bailey as chairman, was widely congratulated on the general arrangements, the type and scope of papers presented, and the high standard of entertainment provided for the several social events.

The Institute of Radio Engineers Cancels National Conventions

In view of wartime transportation conditions, as described by the Office of Defense Transportation, The Institute of Radio Engineers has decided to cancel its 1945 Summer Convention.

As a substitute for this National Convention, the Institute urges its many local sections to conduct local conferences on appropriate special subjects, these conferences to be attended by members residing in the immediate vicinity.

The radio industry is devoted one hundred per cent to war work, including the production of radio, radar, electronic, and other equipment of highly essential nature, much of which is at present secret. The Institute therefore deals entirely with information in a war-essential field. It is nevertheless canceling its 1945 Summer Convention in the further interests of the war effort.

Remarks of Dr. O. H. Caldwell, Editor of *Electronic Industries*, in acknowledging IRE Fellow awards, January 25, to

Dr. H. H. Buttner	Dr. A. L. Loomis	Dr. R. L. Smith-Rose
Dr. O. H. Caldwell	Mr. A. V. Loughren	Dr. K. S. Van Dyke
Dr. W. H. Doherty	Mr. F. X. Rettenmeyer	Captain E. M. Webster
Dr. A. W. Hull	Dr. S. A. Schelkunoff	Mr. P. D. Zottu

Mr. President and Directors of the IRE:

The group of distinguished radio engineers on whom you have conferred the great honor of Fellowship in the Institute, have asked me to express their deep appreciation of this recognition. The new status of "Fellow" you have thus placed upon them will certainly further stimulate their efforts and achievements in the ever-expanding radio art. And it will impose on each an even greater responsibility for service to the industry.

As for myself, I feel very humble at having you pin upon me the title of Fellow. And since "fellow" is a word with many shades of meaning, I determined to look a little into the meaning of the term. So, as a faithful editor, I sought out the dictionaries.

"Fellow," I found, comes from a Medieval English word "felawe." Also an earlier Old English form of the word is revealed in "felaghe." And in light of recent World-War events, one especially interesting result of my search showed that the English apparently got their early term "felaghe" from an even older Icelandic word "felagi." The word thus gives a clue to the early voyages of discovery and commerce between Iceland and England. This bit of etymology reveals, too, how, for many hundreds of years, our English mother tongue has been preparing for this very moment tonight,—by bringing this six-letter word "Fellow" first across ancient arctic seas and then down through the centuries, all intact, for your use on this occasion!

Seeking next for definitions of the word "fellow" in its modern form, Webster, I found, gives several definitions of "fellow." Among them is actually this: "fellow, a man of low breeding or of little worth." Now obviously that definition is hardly the one which you IRE directors meant to imply in connection with these engineers of distinction whom you are honoring tonight.

So I looked further and came onto a more appropriate definition also by Webster: "fellow: a sharer, a partner." That definition of "a sharer, a partner" it seems to me sets the sights and the aims not only for IRE Fellows, old and new, but for all the members of the IRE and of the great radio engineering fraternity.

For never, in all history, has a group of trained engineering specialists been handed such a huge responsibility as has been imposed on radio men in the last two or three years.

Think of this; In 1944 over five billion dollars worth of radio equipment and service—five thousand million dollars—was produced based on the technical discoveries and designs created by the members of the IRE and their predecessor engineers. For each of the voting members of the IRE, there is nearly one and one-half million dollars per man, in 1944. Even more will be produced this year. And all of this five or six billion dollars of actual wealth per year has been created literally out of thin air by radio engineers and radio inventors.

Postwar this huge industry of ours will find new channels and new bases for a useful and expanding existence—of that I have no doubt.

But radio engineers must not be satisfied to be merely employees and staff aids in the huge industries *they* have created. Radio engineers should themselves take business and industrial leadership. It is time for the radio engineer to be the "big boss" of his own concern and shape its general policies. Instead of avoiding and evading business responsibility in order to keep close to the design room and slide rule, radio engineers should prepare themselves to reach out for the top management positions, for independent proprietorships, for public service in fitting radio into broader usefulness to humanity.

All too often, as you and I have observed, some skillful lawyer or clever salesman or quick-minded accountant is chosen to fill the top place in a radio organization, a post which would have been far better served by a trained radio-minded man having the broad grasp necessary to relate our radio art to general business problems.

Radio engineers are perfectionists, I know. And so they like to keep close to their technical work, improving detail parts into the highest possible efficiency.

But even from this aspect of perfectionism alone, you will admit that fullest perfection in radio cannot come unless the radio engineer has the greatest freedom in which to work. And this means that radio engineers at the top must give sympathetic encouragement to radio engineers throughout the organization.

Radio engineers have created a whole galaxy of great industries—industries tremendous in public service, industries imagination-defying in technical achievement, and industries now astronomic in dollar volume!

But these great industries must be officered by radio men, from top executive posts on down to the design rooms and production departments. This is absolutely necessary, for the good of the radio industries and the public they serve. Let me urge therefore, that radio men accept and even seek out these responsibilities of management and direction. Let us take Webster's tip and make the radio engineer a real "sharer and partner" in the huge industries he is creating.

And let us see that the radio man collects in full, for himself and for his family, his share of the wealth he is producing.

The Institute Adds a Chapter to its Survey of Radio Progress

Remarks by L. E. Whittemore, Chair-nan, Annual Review Committee, 1944, efore Winter Technical Meeting, I.R.E., anuary 25, 1945.

The 1944 Chapter of the Institute's Sur-ey of Radio Progress will be the 11th nstallment. The first one related to the year 934 and dealt with (1) fixed (point-to-oint) service, (2) mobile radio service, 3) broadcast transmission, (4) broadcast eception, and (5) fields allied to radio. Each ear since then the Institute has published eviews or surveys of progress in several of he specialized technical fields in which its nembers are interested.

The purpose of these surveys is twofold: irst, to present to the specialist in one field general picture of the important forward teps in the other specialists' fields which he annot follow day by day and, second, to rovide an historical record of the evolution-ry progress in radio communication and llied fields in order that radio engineers nay be better able to view current develop-nents with a proper perspective. The bib-iography, which forms a part of the pub-ished reviews, is believed to be a useful and mportant part of this record.

During recent years, the Annual Review as been a composite of reports prepared by he Institute's several Technical Committees nd it has become the custom for the mem-ership of the Annual Review Committee to onsist of the Chairmen of these technical Committees and two or three other persons vho co-ordinate the material and edit it for ublication.

There would be no point in my going nto a detailed recital of the work of the Annual Review Committee for 1944. You ave just heard the interesting stories pre-ented by the Chairmen of the Technical Committees. The material which they sub-nitted last month for the Annual Survey has een edited and sent to press and you will e able to read it in a forthcoming issue of he PROCEEDINGS. Meanwhile, I am sure we re all making every effort to speed the day vhen, after the war, these survey chapters an have even greater value to those who are nterested in the rapidly expanding fields of adio engineering.

Radio Club Elects Officers

At a recent meeting of The Radio Club of America, announcement was made of the e-election for the 1945 term of the same offi-ers who served during 1944, including three nembers of The Institute of Radio Engi-eers. O. James Morelock (A'35) was reap-ointed vice-president of the Club; M. B. leeper (M'42-SM'43) corresponding secre-ary; and John H. Bose (S'33-A'36), record-ng secretary.

Institute Committees—1945

Admissions

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J. D. Cobine	H. J. Reich
E. D. Cook	C. E. Scholz
M. G. Crosby	S. W. Seeley
Lloyd Espenschied	J. E. Shepherd

M. E. Strieby

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W. L. Barrow	D. E. Harnett
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May 1, 1944, to May 1, 1945

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J. K. Johnson
Garrard Mountjoy
H. O. Peterson
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A. F. Murray
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D. B. Smith

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Case School of Applied Science: P. L. Hoover
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Colorado, University of: J. M. Cage
Columbia University: J. B. Russell
Connecticut, University of: P. H. Nelson
Cooper Union: J. B. Sherman
Cornell University: True McLean

Detroit, University of: A. R. Satullo
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Duke University: W. J. Seeley

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Georgia School of Technology: M. A. Honnell

Harvard University: E. L. Chaffee

Idaho, University of: Hubert Hattrup
Illinois Institute of Technology: C. S. Royce
Illinois, University of: A. J. Ebel
Iowa, University of: L. A. Ware

Johns Hopkins University: Ferdinand Hamburger, Jr.

Kansas State College: Karl Martin
Kansas, University of: G. A. Richardson

Lawrence Institute of Technology: H. L. Byerlay
Lehigh University: C. G. Brennecke
Louisiana State University: Taintor Parkinson

Maine, University of: W. J. Creamer, Jr.
Manhattan College: E. N. Lurch
Maryland, University of: G. L. Davies
Massachusetts Institute of Technology: W. H. Radford and E. Guillemin
McGill University: F. S. Howes
Michigan, University of: L. N. Holland
Minnesota, University of: O. A. Becklund

Nebraska, University of: F. W. Norris
Newark College of Engineering: Solomon Fishman
New York, College of the City of: Harold Wolf
New York University: Philip Greenstein
North Carolina State College: W. S. Carley
North Dakota, University of: E. J. O'Brien
Northeastern University: G. E. Pihl
Northwestern University: A. B. Bronwell
Notre Dame, University of: H. E. Ellithorn

Ohio State University: E. C. Jordan
Oklahoma Agriculture and Mechanical College: H. T. Fristoe
Oregon State College: A. L. Albert

Pennsylvania State College: G. H. Crossley
Pennsylvania, University of: C. C. Chambers
Pittsburgh, University of: L. E. Williams
Princeton University: J. G. Barry
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Utah, University of: O. C. Haycock

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Virginia: Polytechnic Institute: R. R. Wright

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Institute Representatives on Other Bodies—1945

American Documentation Institute: J. H. Dellinger
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ASA Board of Examination: H. P. Westman
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ASA Sectional Committee on Definitions of Electrical Terms: Haraden Pratt
ASA Subcommittee on Vacuum Tubes: B. E. Shackelford
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ASA Sectional Committee on Electrical Measuring Instruments: Wilson Aull, Jr.
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ASA Subcommittee on Letter Symbols for Radio Use: H. M. Turner
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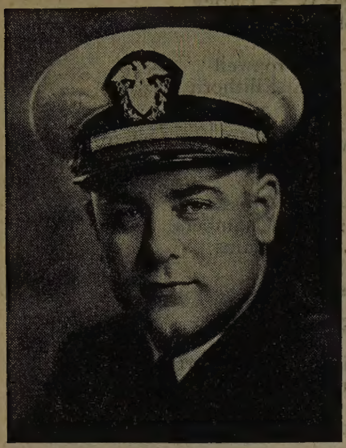
ASA Sectional Committee on Specifications for Dry Cells and Batteries: H. M. Turner
ASA Sectional Committee on Standards for Drawings and Drafting Room Practices: Austin Bailey (H. P. Westman, alternate)
ASA Committee on Vacuum Tubes for Industrial Purposes: B. E. Shackelford
ASA War Committee on Radio: Alfred N. Goldsmith*
ASA War Standards Committee on Methods of Measuring Radio Noise: C. J. Franks and Garrard Mountjoy

* Also chairman of its Subcommittee on Insulating Material Specifications for the Military Services.

Contributors



A. D. Bailey

A. D. Bailey (A'43) was born on February 16, 1915, in Waterloo, Iowa. He received the B.A. degree from Iowa State Teachers College, in 1936; the B.S. degree in electrical engineering from Iowa State College, in 1938; and the M.S. degree in electrical engineering, in 1944, from the University of Illinois.

From 1938 to 1941 he was associated with K. R. Brown, consulting engineer, of Des Moines, Iowa, principally engaged in the design and construction supervision of Rural Electrification Administration lines. He joined the staff of the University of Illinois in 1941, as instructor in electrical engineering, and is at present on leave of absence, serving as an Ensign in the United States Naval Reserve. Mr. Bailey is a member of the American Institute of Electrical Engineers, the Society for Promotion of Engineering Education, and Tau Beta Pi.

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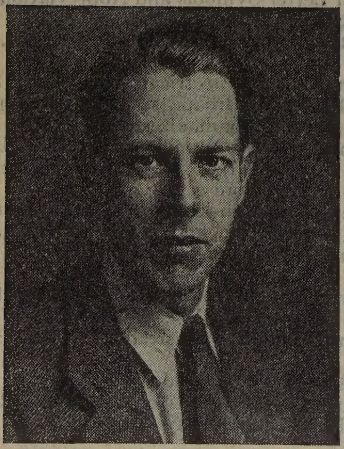

Fitzhugh W. Boggs

Fitzhugh W. Boggs was born at Essex Falls, New Jersey, on December 23, 1911. He had most of his schooling in France where he obtained the degree of Bachelier ès Sciences from the Faculté des Sciences de Marseille. In 1938 he received the B.S. degree from Columbia University. In 1934 he took a position as research technician at the College of Physicians and Surgeons, where he worked on neurological problems under the late Professor Joshua Rosett.

From 1939 to 1942 Mr. Boggs was a graduate student and assistant in chemistry at Cornell University. Since October, 1942, he has been a research engineer in the electronics laboratory of the Westinghouse Electric and Manufacturing Company.

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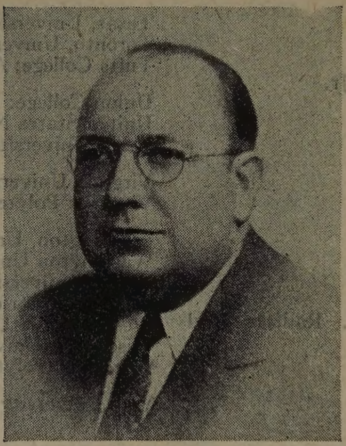
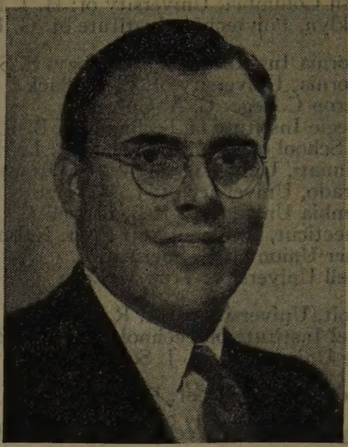


George H. Brown

George H. Brown (A'30-F'42) was born on October 14, 1908, at North Milwaukee, Wisconsin. He received the B.S. degree at the University of Wisconsin in 1930; the degree of M.S. in 1931; the Ph.D. degree in 1933; and his professional degree of E.E. in 1942. From 1930 until 1933 he was a Research Fellow in the electr cal engineering department at the University of Wisconsin, and from 1933 to 1942 he was in the research division of the RCA Manufacturing Company at Camden, New Jersey. Since 1942, he has been at the RCA Laboratories at Princeton, New Jersey. He is a Member of Sigma Xi and the American Institute of Electrical Engineers.

❖

Lloyd B. Cherry (A'44) was born in Weatherford, Texas, on March 1, 1915. He received the B.A. degree in physics from the University of Texas, in 1936, and the M.A. degree from the same institution, in 1937.



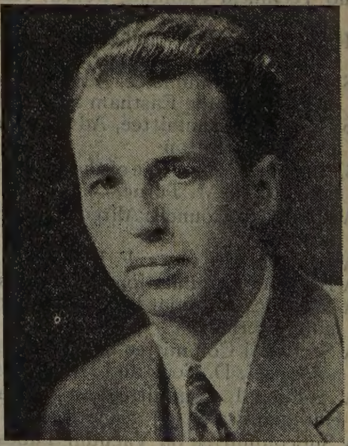
Lloyd B. Cherry

During the summer of 1937, Mr. Cherry was associated with the General Electric Company, in Schenectady, N. Y., and later in the same year joined the commercial engineering department of the Dallas Power and Light Company. From 1938 to 1942 he was instructor of physics and mathematics at Ranger Junior College, Edinburg Junior College, and the University of Texas, where he undertook additional graduate study.

Mr. Cherry joined the research department of the Brown Instrument Company, in 1942, and became engaged in war work directly related to contracts with the Naval Ordnance Laboratory and the Bureau of Ships. He has specialized in the developments of electronic circuits and their mathematical analyses for precision measuring instruments. He is an associate member of Sigma Xi.

❖

W. D. Cockrell received the B.S. degree in electrical engineering from the University of Florida in 1928. Upon graduation, he became associated with the General Electric

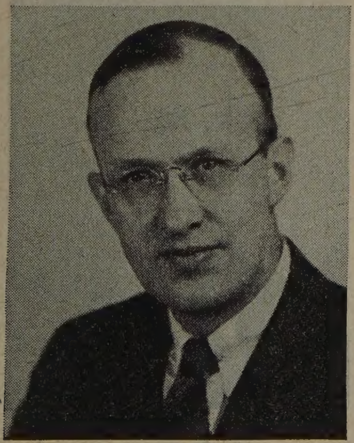


W. D. Cockrell

Thomas W. Dakin

Company, and for thirteen years worked with that organization on design of in-dustrial electronic control, producing 29 patents. Since 1941, Mr. Cockrell has been engaged in electronic application work for the industrial engineering division of the General Electric Company. He is a member of the American Institute of Electrical Engineers, and holds a second-class radio-telephone and WERS license. He is registered as a professional engineer in New York State.

Thomas W. Dakin was born on May 5, 1915, in Minneapolis, Minnesota. He received his A.B. degree in physical chemistry from the University of Minnesota in 1935. From 1935 to 1938 he was a graduate assistant in physical and electrochemistry at Michigan State College, from which institution he received his M.S. degree in 1938. From 1938 to 1941 he held a George Chase Christian Fellowship, and later a Lehman Fellowship, at Harvard University where, in 1941, he received his Ph.D. degree in physical chemistry, completing research on the properties of electrolytic solutions. Since becoming associated with the Westinghouse research laboratories in 1941, he has been for one year a Westinghouse Research Fellow and then a research engineer in the insulation department. His recent research has been on the dielectric properties of plastic materials and the development of high-frequency apparatus for measuring dielectric properties.

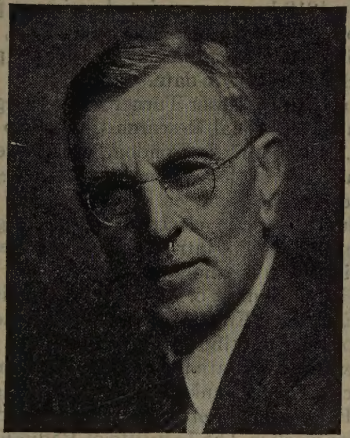


Reuben Lee

G. H. Fett

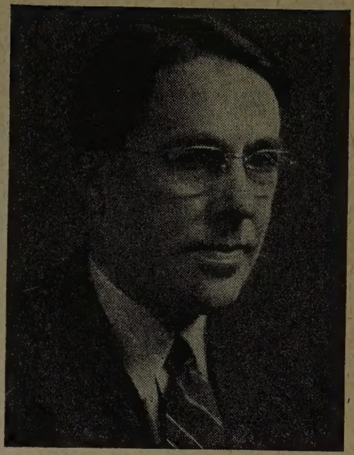
G. H. Fett was born in Chicago, Illinois, on June 19, 1909. He received the B.S. degree in electrical engineering in 1931 from the University of Illinois; the M.S. degree in 1932, from Iowa State College; and the Ph.D. degree in engineering from the University of Illinois, in 1940.

From 1933 to 1935, Dr. Fett was engaged in research work with Littelfuse Laboratories, Chicago, Illinois. He joined the staff of the University of Illinois, in 1935, as assistant in the electrical engineering department. He was subsequently appointed instructor, promoted to the rank of associate, and is at present assistant professor, in that department. He is a member of the American Institute of Electrical Engineering, the American Physical Society, the American Welding Society, Sigma Xi, and Tau Beta Pi.



I. E. Mouromtseff

Reuben Lee (A'32) was born on November 8, 1902, at Shirland, Derbyshire, England. He received the B.S. degree in electrical engineering from West Virginia University in 1924. Upon graduation, he became associated with the Westinghouse Electric and Manufacturing Company, first in the student course, followed, in 1925, by the control engineering department, and transferring to the radio engineering department in 1928. Mr. Lee is now a design engineer in the Baltimore plant of that organization. He is a member of Tau Beta Pi.

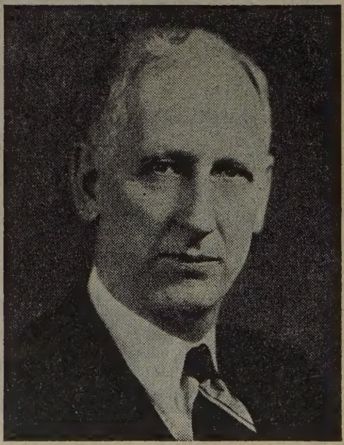


Arthur L. Samuel

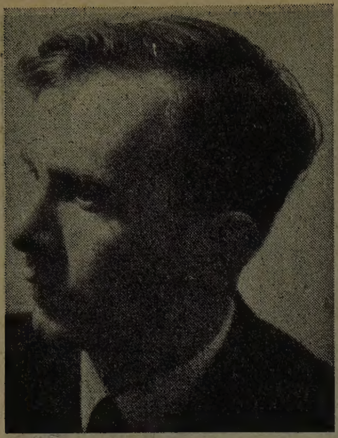
I. E. Mouromtseff (A'34) was born in December, 1881, at St. Petersburg, Russia. He received the M.E. degree from the Engineering Academy, St. Petersburg, in 1906, and in 1910 was awarded the Diploma-Ingenieur degree in electrical engineering from the Grand Ducal Institute of Technology, Darmstadt, Germany. During the following year he was dean of the Signal Corps School for Army Officers, in Russia. In 1911 Mr. Mouromtseff was a member of the Franco-Russian Radio Committee.

In 1923 he became affiliated with the Westinghouse Electric and Manufacturing Company in the research laboratories at East Pittsburgh. He was transferred to the vacuum-tube department in 1936, and since 1942 has worked in the electronics engineering department, in Bloomfield, N. J.

Arthur L. Samuel (A'24-SM'44) was born at Emporia, Kansas, on December 5, 1901. He received the A.B. degree from the College of Emporia in 1923, the degrees of S.B. and S.M. in electrical engineering from the Massachusetts Institute of Technology in 1926, and has done additional graduate



Hubert M. Turner



E. E. Suckling

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work both at M.I.T. and at Columbia University. He was employed by the General Electric Company intermittently from 1923 to 1927, and was an instructor in the electrical engineering department at the Massachusetts Institute of Technology from 1926 to 1928. Mr. Samuel joined the technical staff of the Bell Telephone Laboratories in 1928, and was engaged in electronic research and development. Since 1931, his principal interest has been in the development of vacuum tubes for use at ultra-high frequencies. He is a member of the American Physical Society and of the American Institute of Electrical Engineers.

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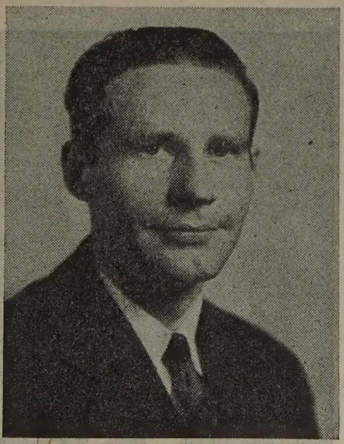
E. E. Suckling* was born in Auckland, New Zealand, on August 4, 1915. He received the M.Sc. degree in physics, with a thesis on radio-frequency soil constants. He joined the telecommunication section of the Post and Telegraph Department of the New Zealand government and spent two years in the test laboratory. Mr. Suckling was then transferred to the radio section of the same department, where he has covered a wide variety of projects concerned with radio-station installations. He has also been responsible for a considerable amount of equipment design and development work.

* Paper published in January, 1945, issue of the Proceedings



O. M. Woodward, Jr.

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H. M. Turner (A'14-M'20-F'37) was born on July 20, 1882, at Hillsboro, Illinois. He received the B.S. degree in electrical engineering from the University of Illinois in 1910, and remained as assistant instructor for two years while doing graduate study. He received the Master's degree in 1915.

From 1912 to 1918, Professor Turner was instructor at the University of Minnesota, and organized courses in transient phenomena and radio. During the First World War he was placed in charge of technical instruction of the Signal Corps unit of enlisted men at the University of Minnesota, and in 1918 became assistant professor of radio with the Signal Corps School for Officer Candidates at Yale University.

In 1919 he was appointed assistant professor of electrical engineering at Yale, becoming associate professor in 1926, a post which he has held to date.

In 1934 Professor Turner was a delegate from the National Research Council to the U.R.S.I. meeting in London, and delivered a paper on high-frequency measurements. Since 1935 he has been in charge of all the graduate work in electrical engineering at Yale, and has also introduced electrical engineering to Yale juniors.

He is a member of the American Institute of Electrical Engineers, the International Union of Scientific Radio Telegraphy, the American Association for the Advancement of Science, the Franklin Institute, and Sigma Xi. Professor Turner has been active in committee work in The Institute of Radio Engineers on matters relating to standardization, technical papers, instruments and measurements, and communications. He was President of the Institute during 1944.

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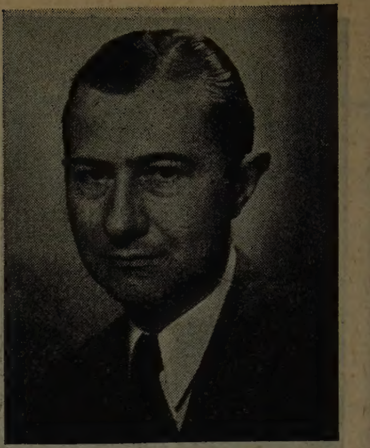
Rudolf F. Wild (A'37) was born in New York City, on August 27, 1910. He received the M.S. degree in communications engineering from Berlin Institute of Technology in 1935, and became associated with the research group of Farnsworth Television, Inc., at Philadelphia, Pa. In 1939 Farnsworth Television, Inc., was reorganized and transferred to Fort Wayne, Ind., under the new name of Farnsworth Television and Radio Corporation. At that time Mr. Wild became research consultant and patent engineer for the new organization, remaining in that capacity until 1941, when he joined the patent department of Zenith Radio Corporation in Chicago, Ill.

Since 1942 he has been chief electronic research engineer for the Brown Instrument Company of Philadelphia, supervising the design and development of electronic equipment for use with precision measuring instruments.



Rudolf F. Wild

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O. M. Woodward, Jr. (S'38-A'40) was born on January 13, 1915, at Davis, Oklahoma. After receiving the degree of Bachelor of Science in electrical engineering from the University of Oklahoma in 1938, he joined the Seismograph Service Corporation of Tulsa, Oklahoma. During 1941 Mr. Woodward was a research engineer at the RCA Manufacturing Company, Camden, New Jersey. Since January 1, 1942, he has been with RCA Laboratories, Princeton, New Jersey. He is a member of Sigma Xi.

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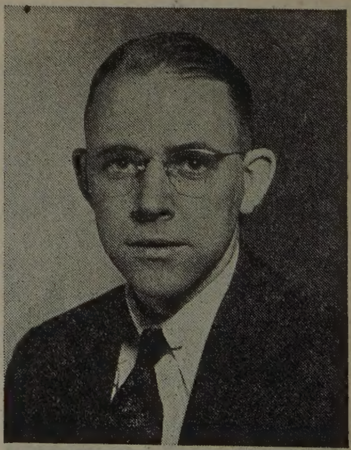
C. N. Works was born at Fairfield, Maine, on July 7, 1910. He received the B.S. degree in electrical engineering from the University of Maine, in 1934. He was employed as a student engineer by Phelps Dodge Copper Products Corporation, Elizabeth, N. J., and later became a research engineer for the Habirshaw cable and wire division of the same company, at Yonkers, New York. Since December, 1942, he has been a research engineer in the insulation department of the research laboratories, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pennsylvania. Concurrently, with his employment at the Westinghouse Electric and Manufacturing Company, he has been a graduate student at the University of Pittsburgh.



C. N. Works